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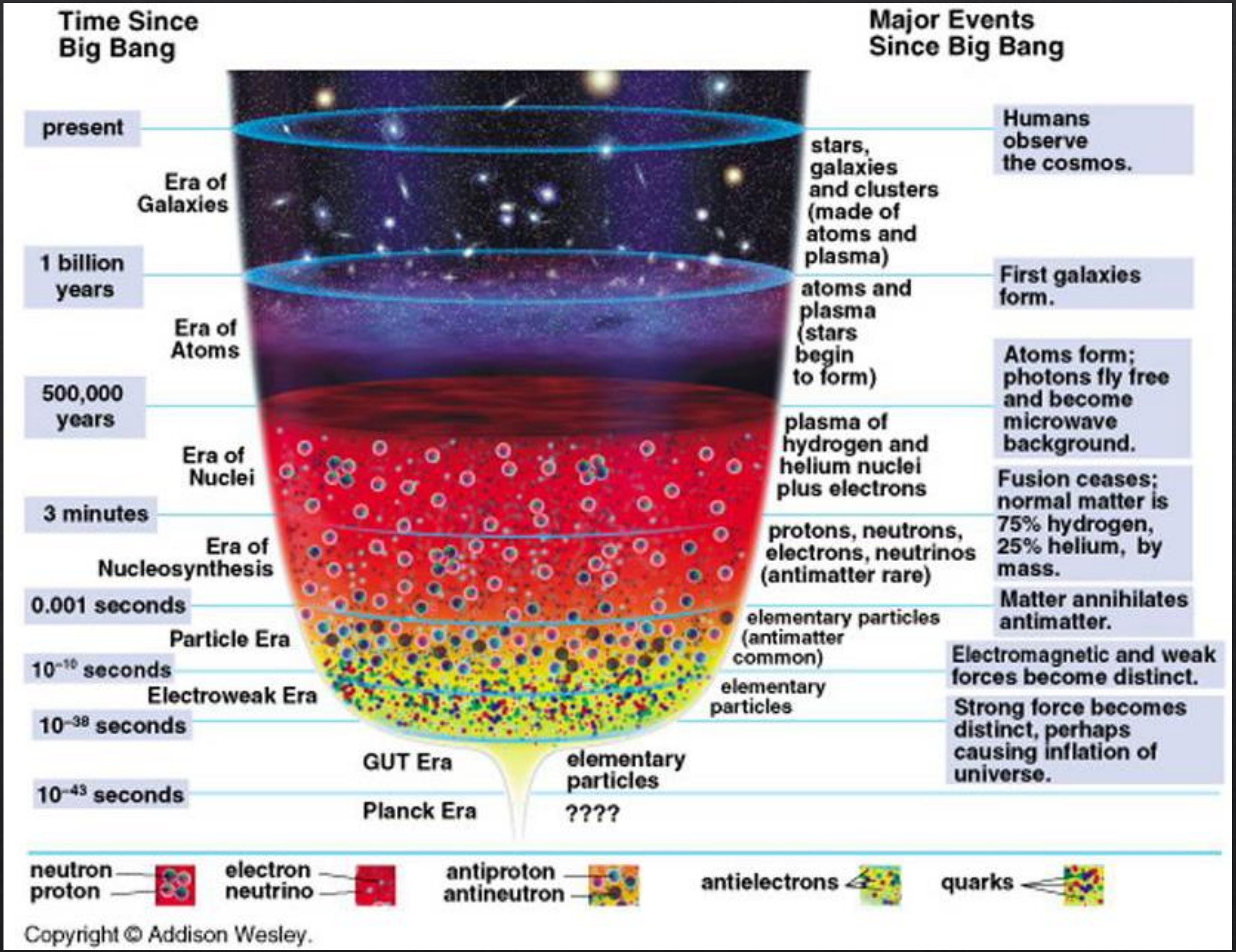
Introducere în fizica particulelor la energii înalte

„CERN **Romanian High-School Students Internship Programme 2024** "

4 iunie 2024

Introducere

- **Din ce este constituită materia?**
- **Din ce este compus universul?**
- **Care este originea universului și cum a evoluat?**
- **De ce se comportă așa universul?**
- **Cum va evolua?**
- **....**

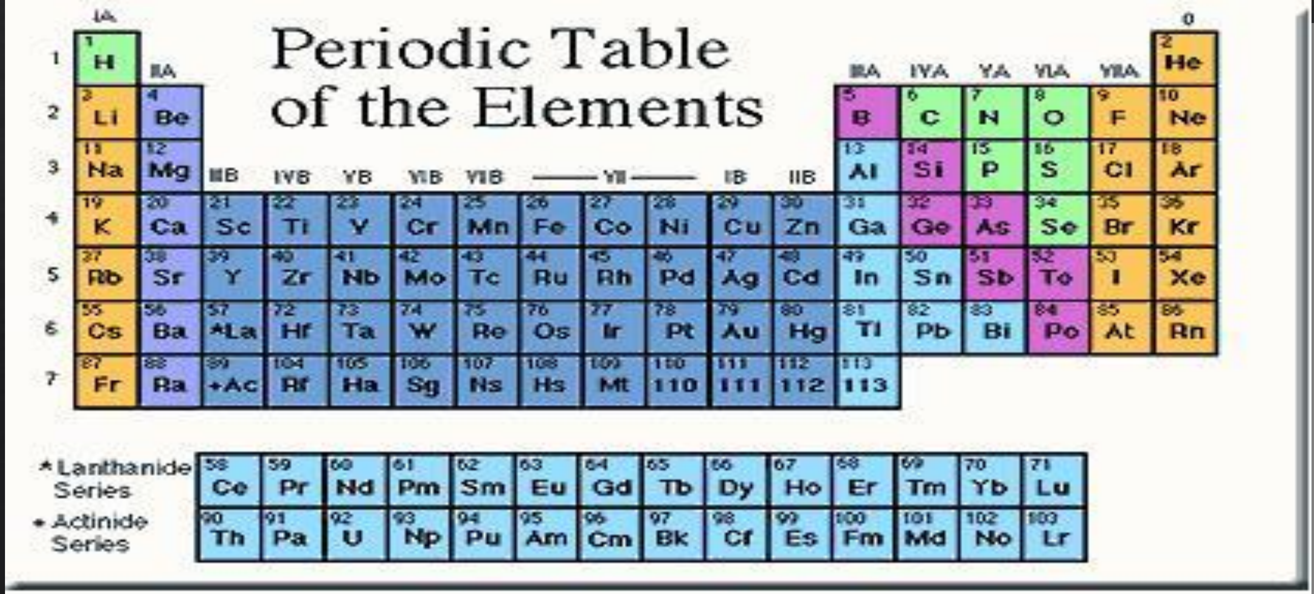

Time Since Big Bang
Major Events Since Big Bang
present
Era of Galaxies
1 billion years
Era of Atoms
500,000 years
Era of Nuclei
3 minutes
Era of Nucleosynthesis
0.001 seconds
Particle Era
10^{-10} seconds
Electroweak Era
10^{-38} seconds
GUT Era
10^{-43} seconds
Planck Era
stars, galaxies and clusters (made of atoms and plasma)
atoms and plasma (stars begin to form)
plasma of hydrogen and helium nuclei plus electrons
protons, neutrons, electrons, neutrinos (antimatter rare)
elementary particles (antimatter common)
elementary particles
elementary particles
????
Humans observe the cosmos.
First galaxies form.
Atoms form; photons fly free and become microwave background.
Fusion ceases; normal matter is 75% hydrogen, 25% helium, by mass.
Matter annihilates antimatter.
Electromagnetic and weak forces become distinct.
Strong force becomes distinct, perhaps causing inflation of universe.
neutron
proton
electron
neutrino
antiproton
antineutron
antielectrons
quarks
Copyright © Addison Wesley.

Care sunt elementele din care este constituita materia?

Empedocles 492-432 BC

By convention there is color,
by convention sweetness,
by convention bitterness,
but in reality there are
atoms and space.

Democritus 400 BC



Mendeleev, 1869

Scurt istoric

- sfârșitul secolului XIX:
  - mecanică clasică;
  - electromagnetism;
  - termodinamică.

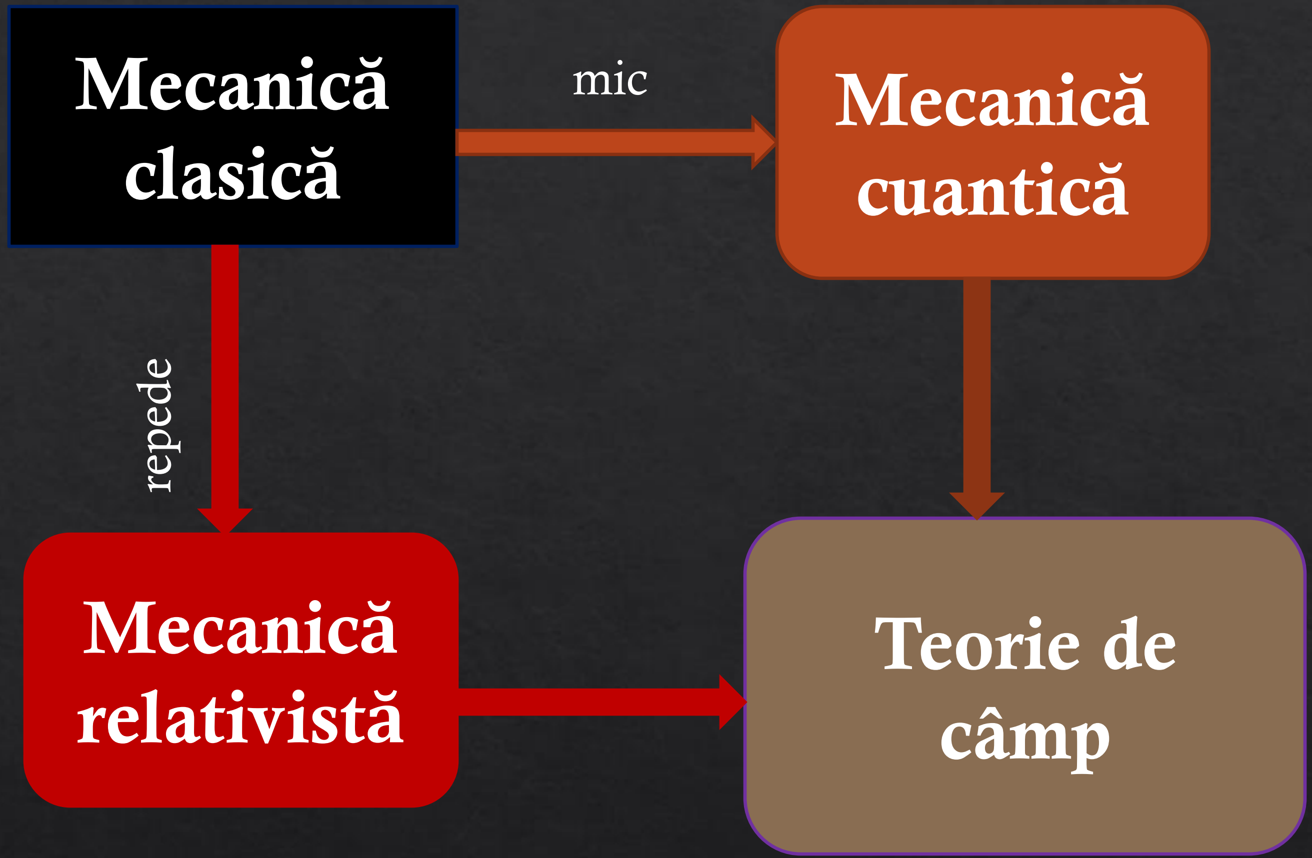
- începutul secolului XX:
  - domeniul relativist (mecanica Newtoniană nu poate fi folosită la viteze foarte mari)
  - domeniul microscopic (fizica clasică nu poate fi folosită la nivel microscopic – e.g. pentru descrierea atomilor și moleculelor, a interacției cu câmpul electromagnetic etc.)

Ce legi folosim?

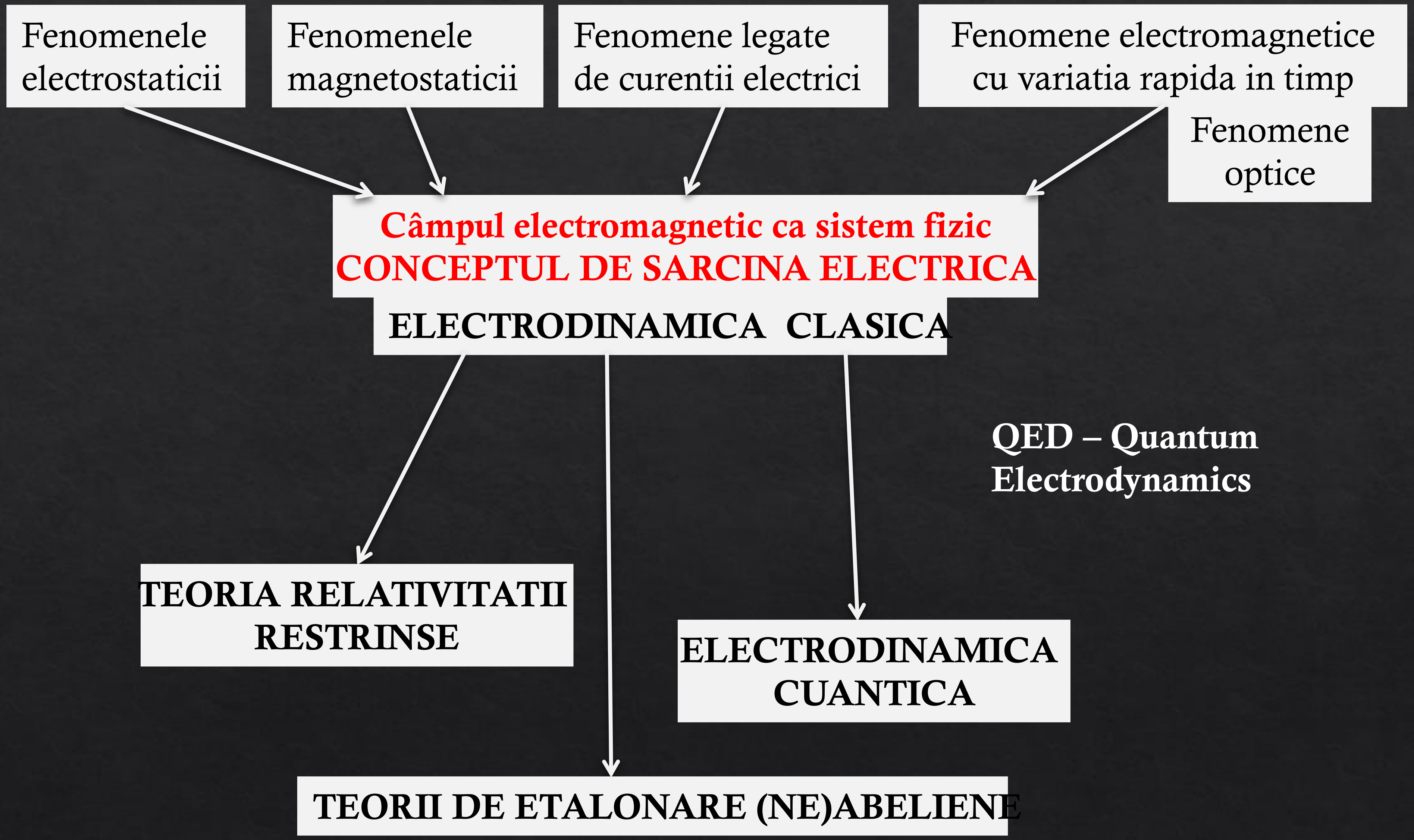
Ce mecanică folosim?

Legea atracției universale

Legile de mișcare ale lui Newton – mecanica clasică

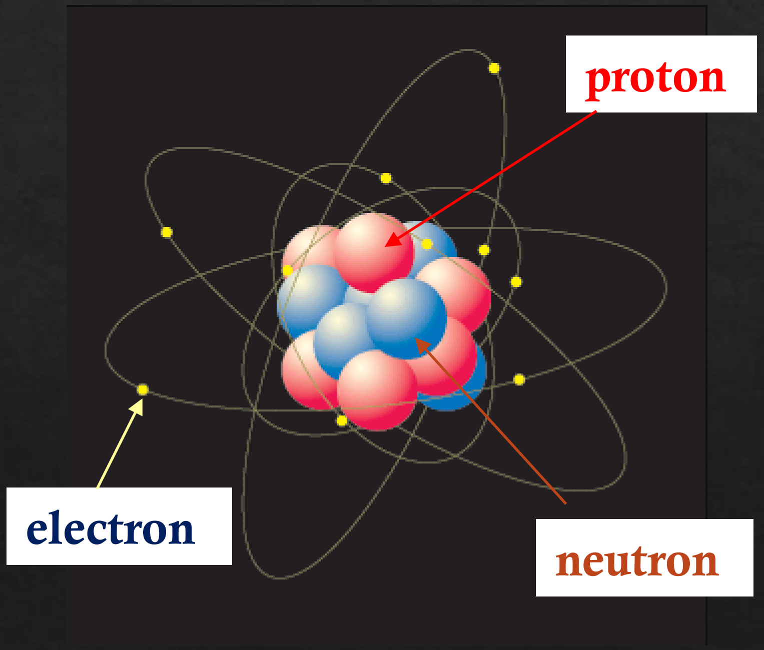

Mecanică clasică
mic
Mecanică cuantică
repede
Mecanică relativistă
Teorie de câmp

Câmpul electromagnetic ca sistem fizic



Atomii

Atomii:
- protoni și neutroni în nucleu
- electroni



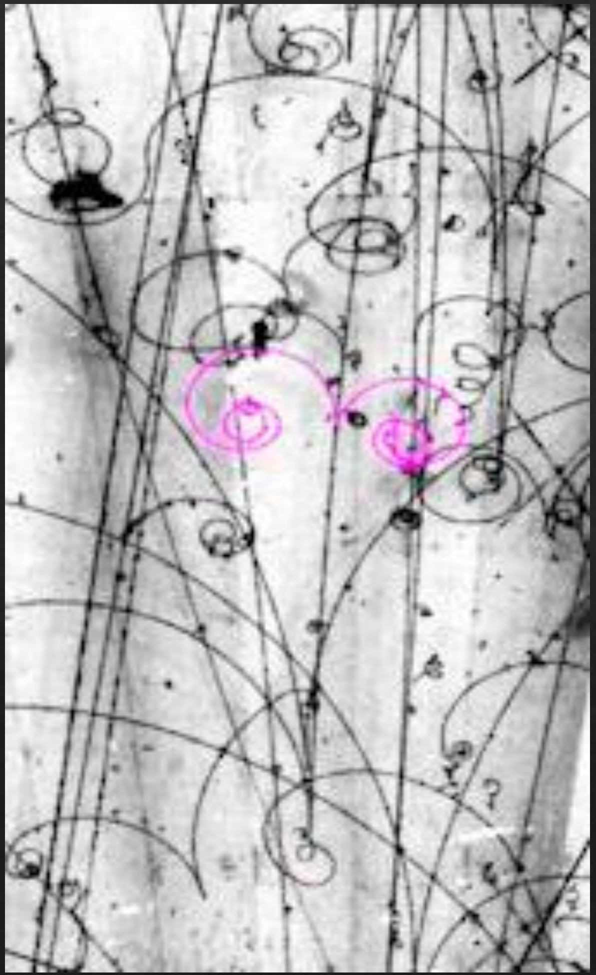
Sunt protonii și neutronii particule elementare?

Fizica particulelor elementare

1. Care sunt particulele elementare (ce proprietăți au – masă, sarcină electrică, spin, ...)?
2. Cum interacționează?
3. Cum producem particule elementare?
4. Cum detectăm particule elementare?

Dirac – particulă - antiparticulă

sarcină electrică
de semn opus



- Pereche electron-positron creată din fotoni într-o cameră cu bule.
- Energia fotonului este transformată în
•materie și anti-materie.

- Energia și impulsul se conservă (dar nu și masa de repaus)

Yukawa – 1934

- Ce ține protonii și neutronii în nucleul?

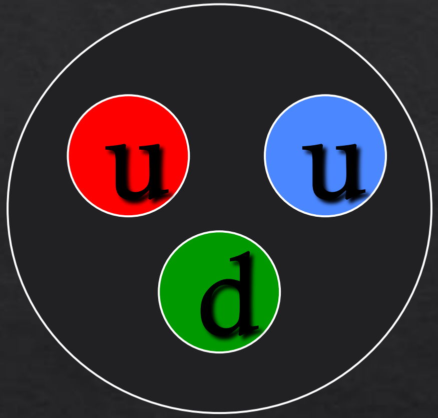
INTERACȚIA TARE

- De ce nu o experimentăm în viața de zi cu zi?

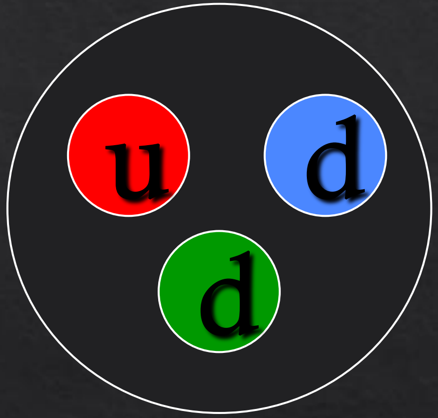
acționează la distanțe scurte

Protonii și neutronii – modelul cuarcilor (1964)

proton (sarcină +1)



neutron (sarcină 0)



Cuarcii au sarcini electrice fracționare

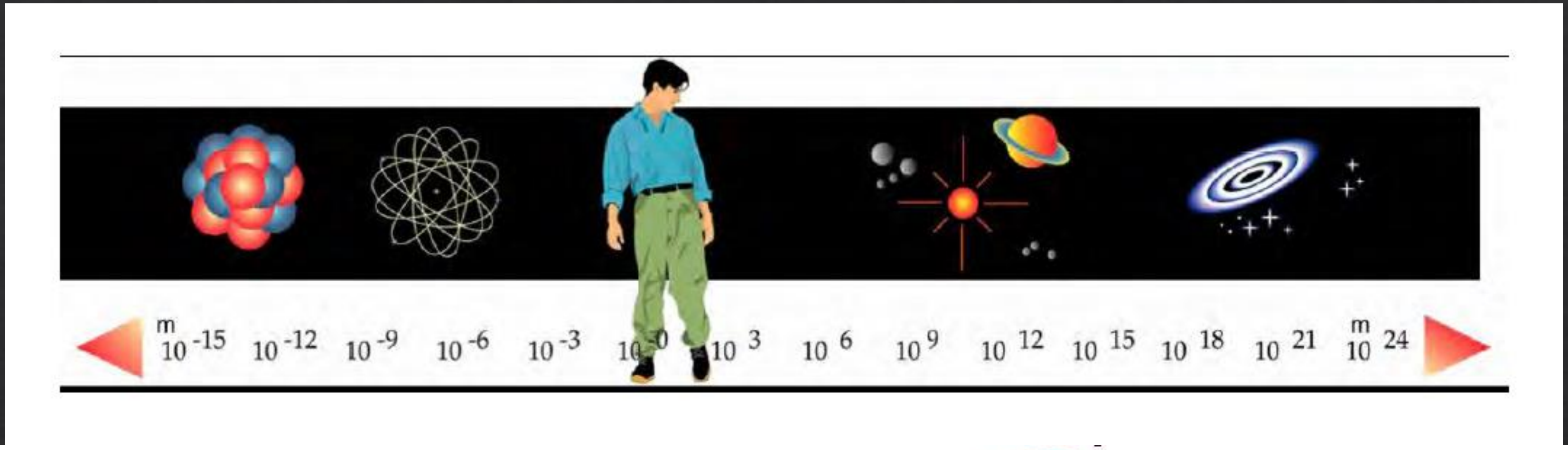
u - cuarcul up – sarcină electrică + 2/3

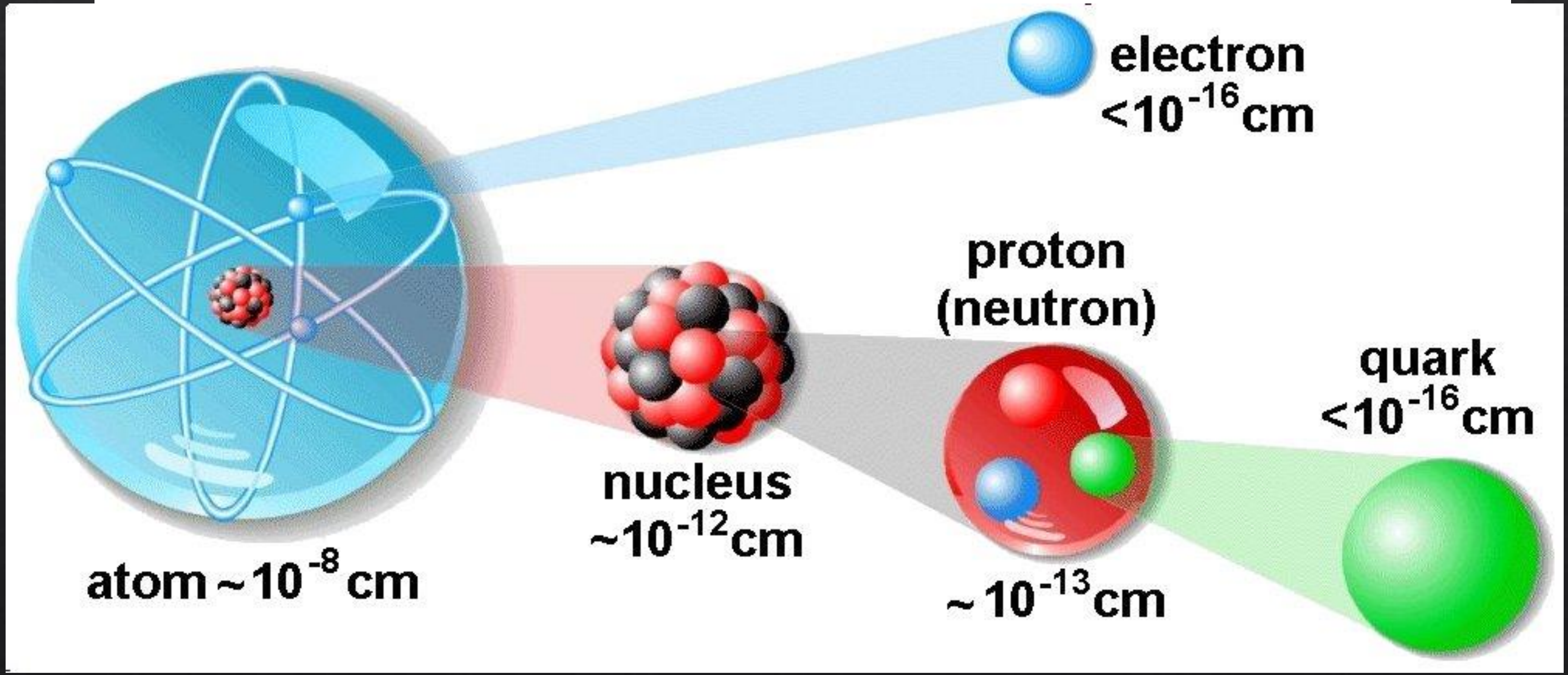
d - cuarcul down – sarcină electrică –1/3

$$u\left(+\frac{2}{3}\right)u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)=p(+1)$$

$$u\left(+\frac{2}{3}\right)d\left(-\frac{1}{3}\right)d\left(-\frac{1}{3}\right)=n(0)$$

Structura materiei (astăzi!)

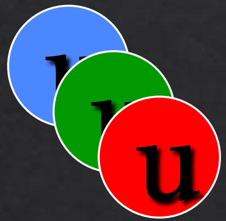




Cuarcii și culorile

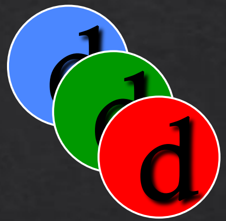
QCD – Quantum chromodynamics

Fiecare cuarc poate avea 3 "culori"



up

+2/3



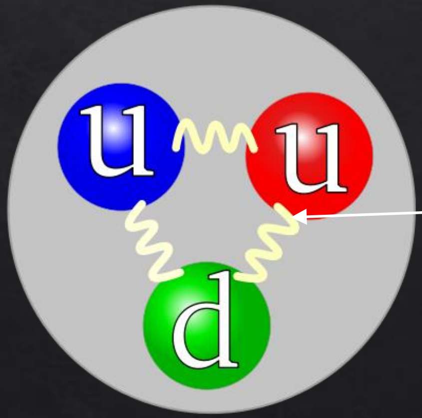
down

-1/3

Cuarcii se combină în așa fel încât să formeze particule „incolore" (confinare).

-Barioni (3 cuarci qqq: roșu + verde + albastru = alb)

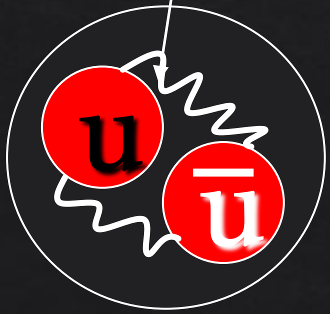
proton
p



interacția tare - "lipește" cuarcii în stări legate -

-Mezoni (cuarc-anticuarc qqbar)

pion
π



PDG – Particle Data Group

STRANGE MESONS

K_L^0	130
K_S^0	310
K^0	311
K^+	321
$K_0^*(800)^0$	**9000311***
$K_0^*(800)^+$	**9000321***
$K_0^*(1430)^0$	10311
$K_0^*(1430)^+$	10321
$K(1460)^0$	100311
$K(1460)^+$	100321
$K(1830)^0$	**9010311***
$K(1830)^+$	**9010321***
$K_0^*(1950)^0$	**9020311***
$K_0^*(1950)^+$	**9020321***
$K^*(892)^0$	313
$K^*(892)^+$	323
$K_1(1270)^0$	10313
$K_1(1270)^+$	10323
$K_1(1400)^0$	20313
$K_1(1400)^+$	20323
$K^*(1410)^0$	100313
$K^*(1410)^+$	100323
$K_1(1650)^0$	**9000313***
$K_1(1650)^+$	**9000323***
$K^*(1680)^0$	30313

CHARMED MESONS

D^+	411
D^0	421
$D_0^*(2400)^+$	10411
$D_0^*(2400)^0$	10421
$D^*(2010)^+$	413
$D^*(2007)^0$	423
$D_1(2420)^+$	10413
$D_1(2420)^0$	10423
$D_1(H)^+$	20413
$D_1(2430)^0$	20423
$D_2^*(2460)^+$	415
$D_2^*(2460)^0$	425
D_s^+	431
$D_{s0}^*(2317)^+$	10431
D_s^{*+}	433
$D_{s1}(2536)^+$	10433
$D_{s1}(2460)^+$	20433
$D_{s2}^*(2573)^+$	435

BOTTOM MESONS

B^0	511
B^+	521
B_0^{*0}	10511
B_0^{*+}	10521
B^{*0}	513

$c\bar{c}$ MESONS

$\eta_c(1S)$	441
$\chi_{c0}(1P)$	10441
$\eta_c(2S)$	100441
$J/\psi(1S)$	443
$h_c(1P)$	10443
$\chi_{c1}(1P)$	20443
$\psi(2S)$	100443
$\psi(3770)$	30443
$\psi(4040)$	9000443
$\psi(4160)$	9010443
$\psi(4415)$	9020443
$\chi_{c2}(1P)$	445
$\chi_{c2}(2P)$	**100445***

$b\bar{b}$ MESONS

$\eta_b(1S)$	551
$\chi_{b0}(1P)$	10551
$\eta_b(2S)$	100551
$\chi_{b0}(2P)$	110551
$\eta_b(3S)$	200551
$\chi_{b0}(3P)$	210551
$\Upsilon(1S)$	553
$h_b(1P)$	10553
$\chi_{b1}(1P)$	20553
$\Upsilon_1(1D)$	30553

LIGHT BARYONS

p	2212
n	2112
Δ^{++}	2224
Δ^+	2214
Δ^0	2114
Δ^-	1114

STRANGE BARYONS

Λ	3122
Σ^+	3222
Σ^0	3212
Σ^-	3112
Σ^{*+}	3224^d
Σ^{*0}	3214^d
Σ^{*-}	3114^d
Ξ^0	3322
Ξ^-	3312
Ξ^{*0}	3324^d
Ξ^{*-}	3314^d
Ω^-	3334

CHARMED BARYONS

Λ_c^+	4122
Σ_c^{++}	4222
Σ_c^+	4212
Σ_c^0	4112
Σ_c^{*++}	4224
Σ_c^{*+}	4214

BOTTOM BARYONS

Λ_b^0	5122
Σ_b^-	5112
Σ_b^0	5212
Σ_b^+	5222
Σ_b^{*-}	5114
Σ_b^{*0}	5214
Σ_b^{*+}	5224
Ξ_b^-	5132
Ξ_b^0	5232
$\Xi_b^{\prime -}$	5312
$\Xi_b^{\prime 0}$	5322
Ξ_b^{*-}	5314
Ξ_b^{*0}	5324
Ω_b^-	5332
Ω_b^{*-}	5334
Ξ_{bc}^0	5142
Ξ_{bc}^+	5242
$\Xi_{bc}^{\prime 0}$	5412
$\Xi_{bc}^{\prime +}$	5422
Ξ_{bc}^{*0}	5414
Ξ_{bc}^{*+}	5424
Ω_{bc}^0	5342
$\Omega_{bc}^{\prime 0}$	5432

Universul este alcătuit numai din cuarci și electroni?

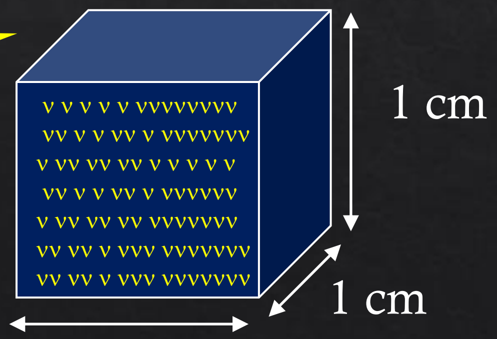
Există și neutrini!

ν

Electronul, protonul și neutronul sunt rari!
Pentru fiecare dintre ei, există1 billion neutrini.

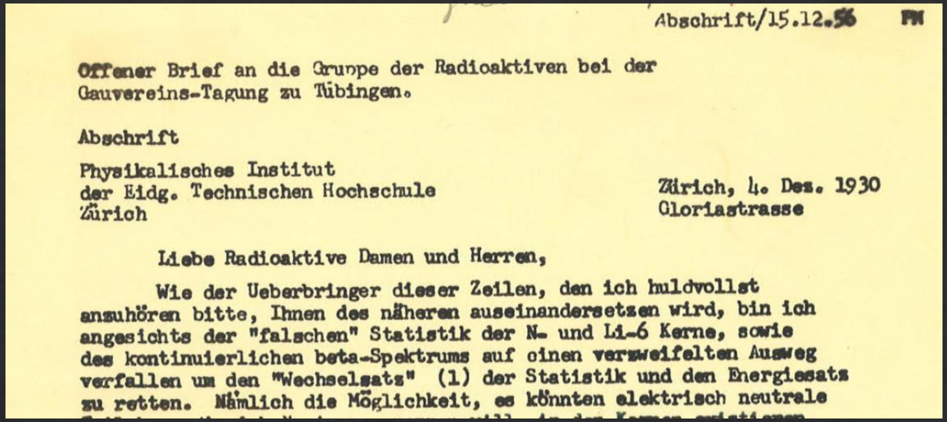
Neutrinii sunt cele mai abundente particule ale materiei în univers.

În fiecare cm^3 al spațilui sunt ~300 neutrini de la Big Bang



Neutrinii sunt peste tot.

Dezintegrarea β


Abschrift/15.12.56 PM

Offener Brief an die Gruppe der Radioaktiven bei der
Gauvereins-Tagung zu Tübingen.

Abschrift

Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

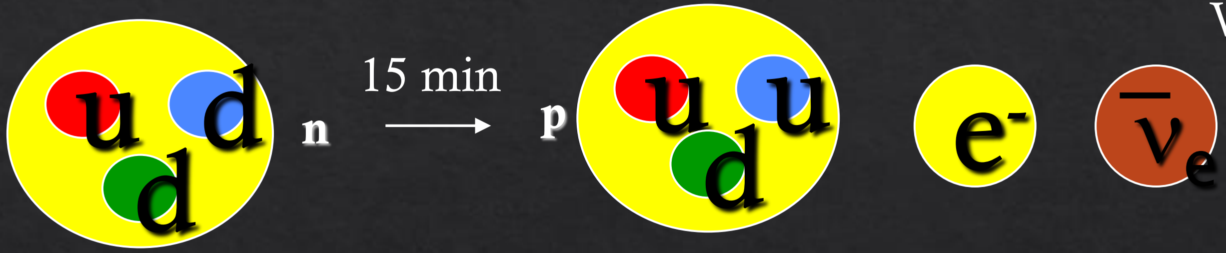
Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale

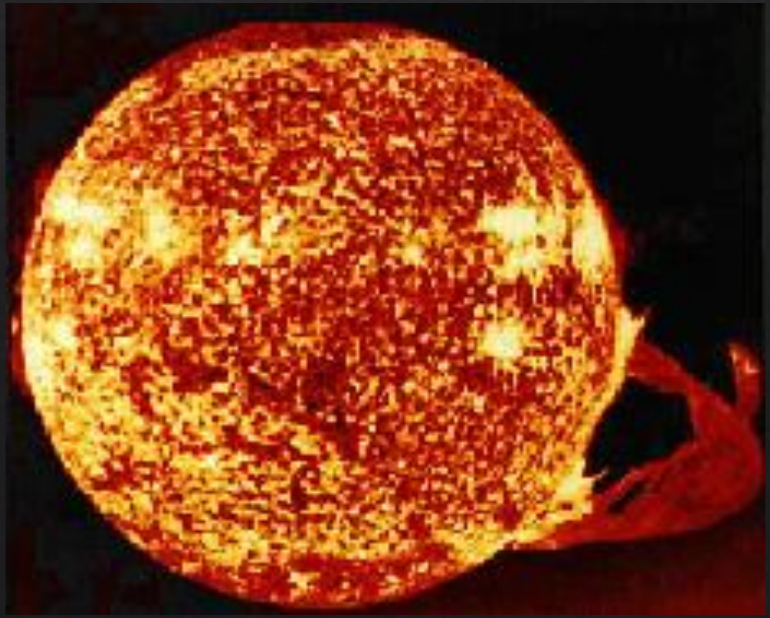
W.Pauli - 1930

La nivelul cuarcilor: $d \rightarrow u\, e^- \bar{\nu}_e$



Un neutron se dezintegrează în 15 minute.

interacție „slabă”!



QFD – Quantum flavordynamics

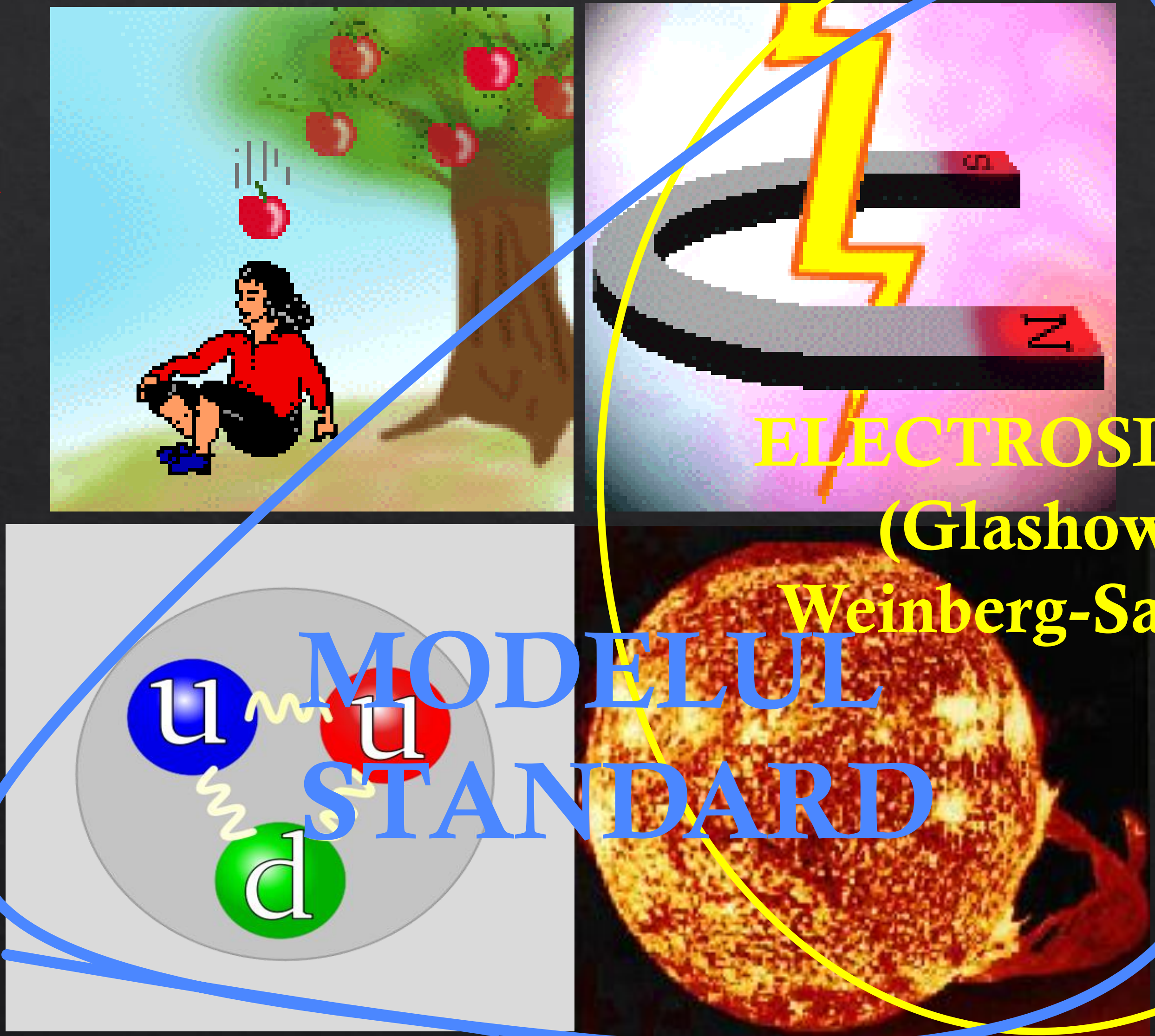
!

Tipuri de interacție

Gravitațională

masa

Electromagnetică



Tare

Slabă

Cine mediază interacțiile?

bozonii

Gravitațională

? graviton ?

QED – Quantum Electrodynamics

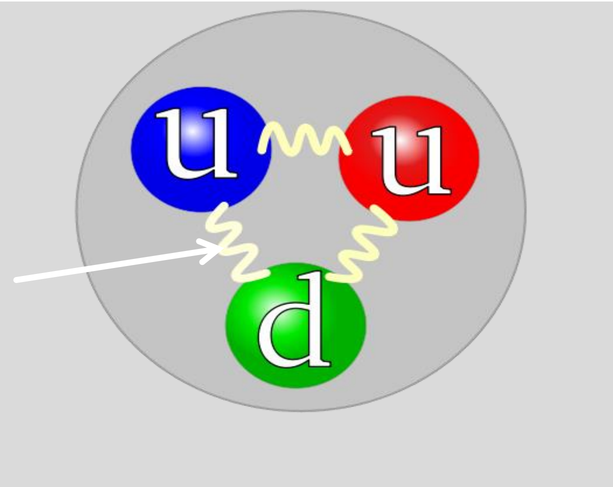
Electromagnetică

γ- fotonul

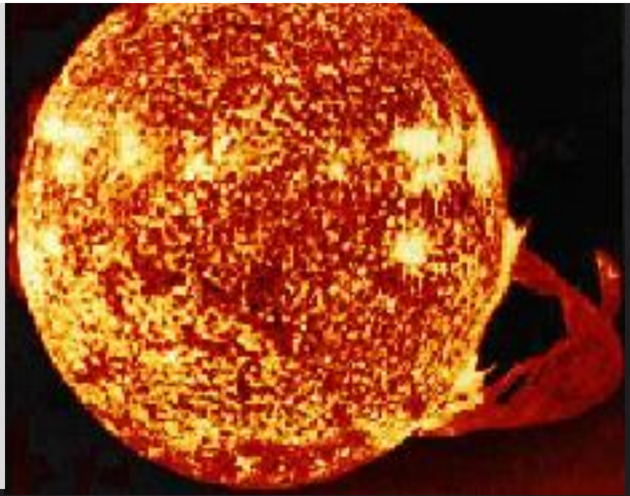
$$G_{SM} = SU(3)_C \times SU(2)_L \times U(1)_Y \rightarrow SU(3)_C \times U(1)_Q$$

Tare

gluonii



QCD – Quantum chromodynamics



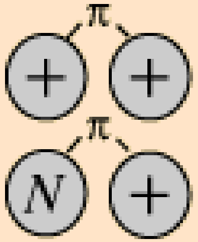
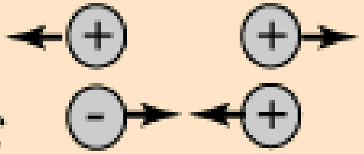
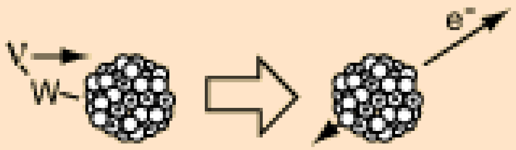
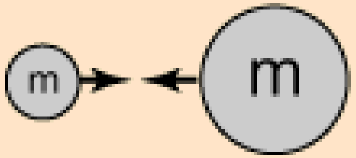
QFD – Quantum flavordynamics

Slabă

W^+, W^-, Z

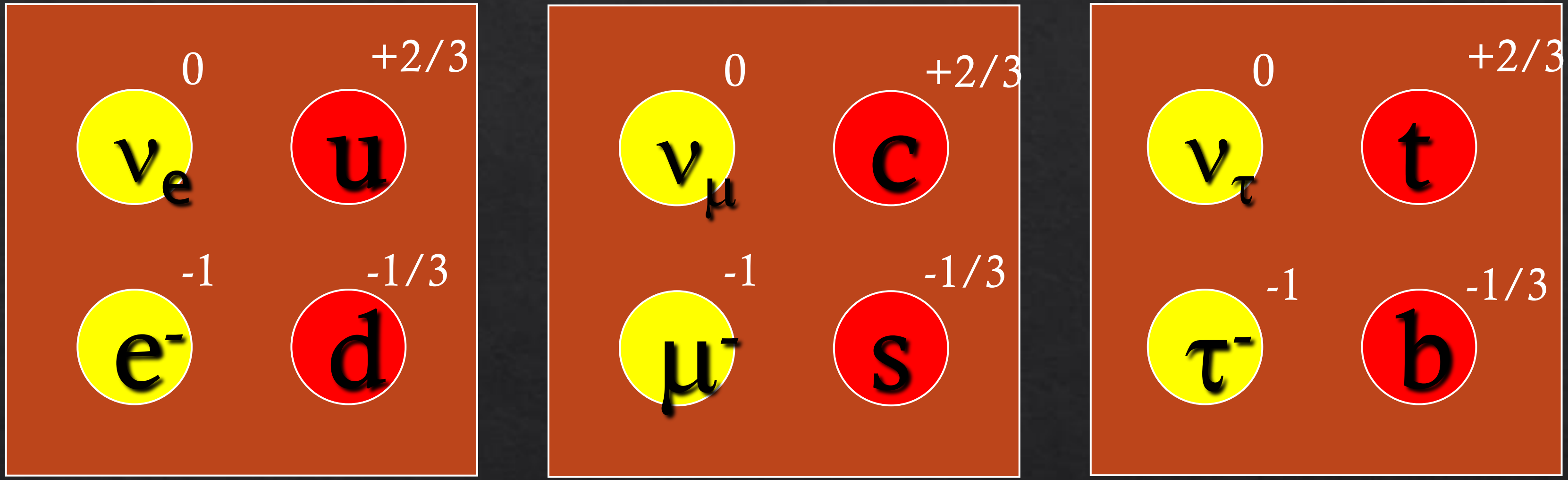
Fundamental Forces

http://hyperphysics.phy-astr.gsu.edu/hbase/Forces/funfor.html

Force		Strength	Range (m)	Particle
Strong	 Force which holds nucleus togeher	1	10^{-15} (diameter of a medium sized nucleus)	gluons, π(nucleons)
Electro-magnetic		$\frac{1}{137}$	Infinite	photon mass = 0 spin = 1
Weak	 neutrino interaction induces beta decay	10^{-6}	10^{-18} (0.1% of the diameter of a proton)	Intermediate vector bosons W^+, W^-, Z_0, mass > 80 GeV spin =1
Gravity		6×10^{-39}	Infinite	graviton ? mass = 0 spin = 2

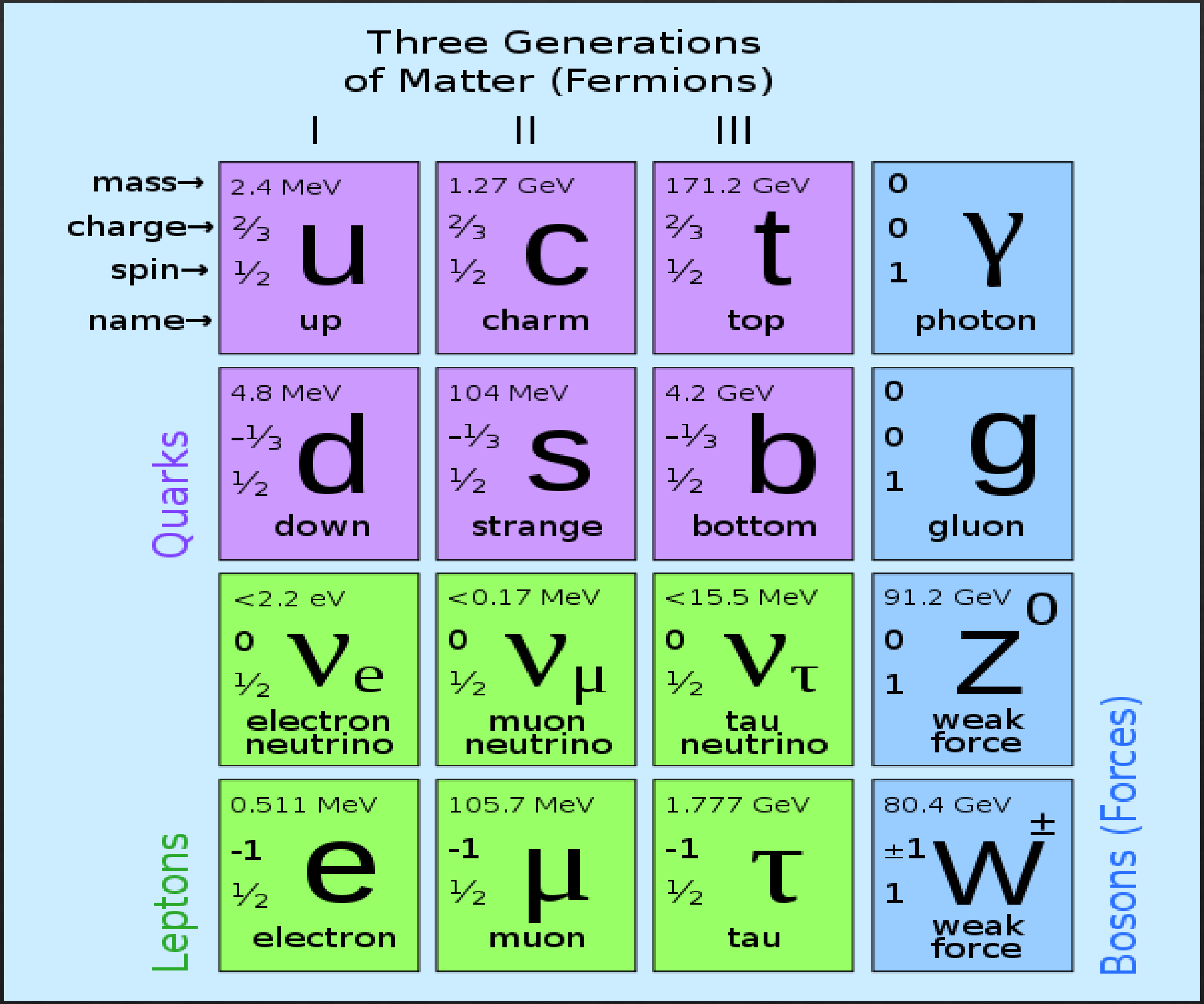
3 FAMILII (ASTĂZI!)

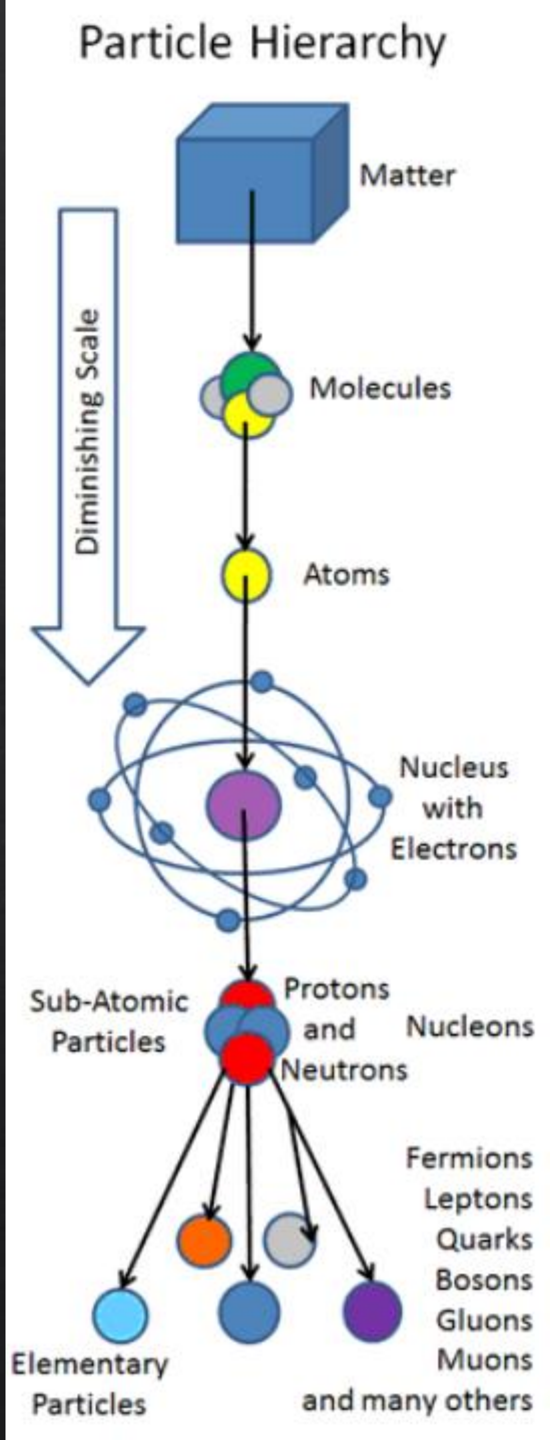
prima generație | a doua generație | a treia generație

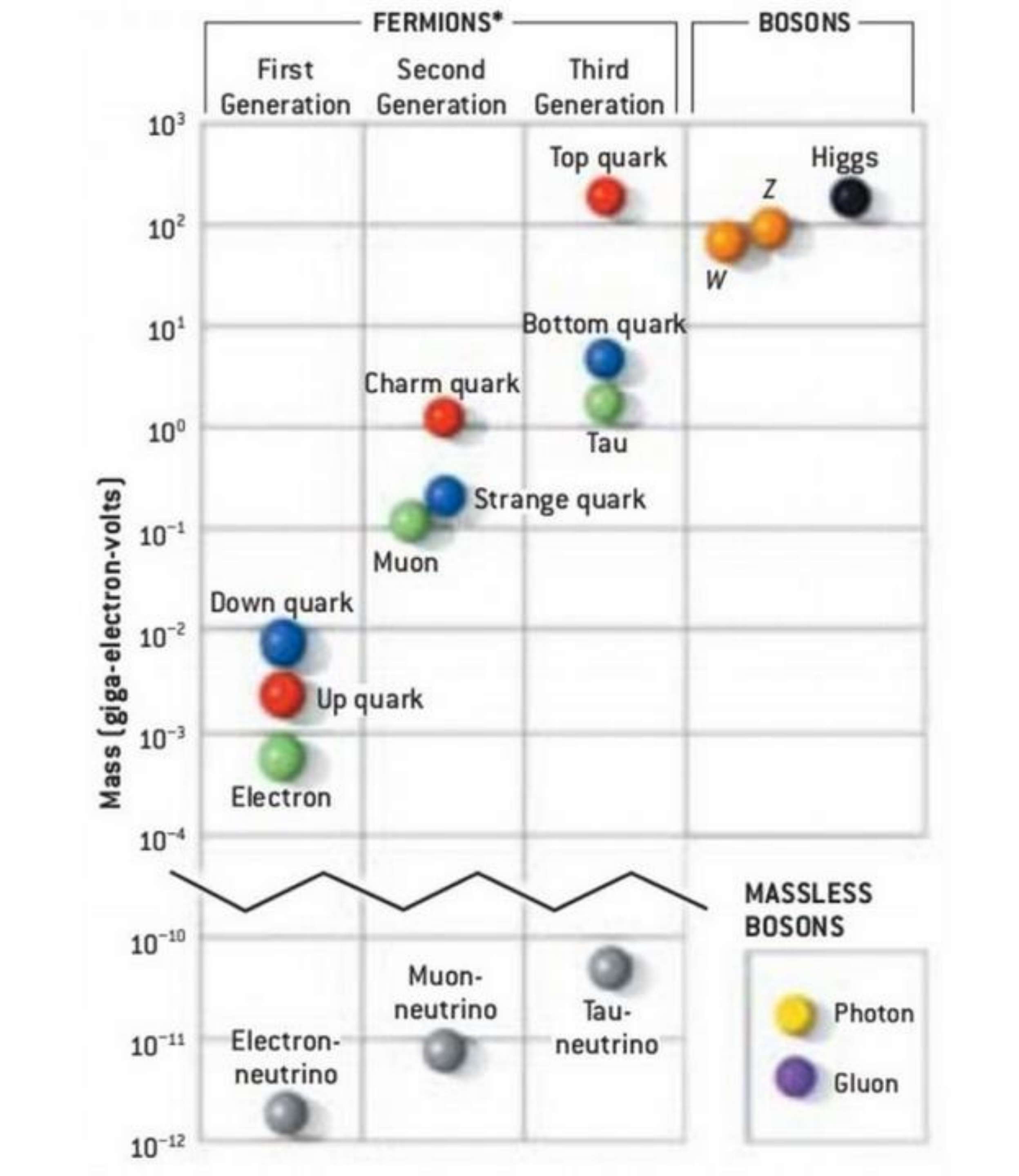


materie „obișnuită” | radiație cosmică | acceleratori

cele 3 generații diferă prin masă!


Three Generations
of Matter (Fermions)
I
II
III
mass→
charge→
spin→
name→
2.4 MeV
2/3
1/2
u
up
1.27 GeV
2/3
1/2
c
charm
171.2 GeV
2/3
1/2
t
top
0
0
1
γ
photon
Quarks
4.8 MeV
-1/3
1/2
d
down
104 MeV
-1/3
1/2
s
strange
4.2 GeV
-1/3
1/2
b
bottom
0
0
1
g
gluon
<2.2 eV
0
1/2
νe
electron neutrino
<0.17 MeV
0
1/2
νμ
muon neutrino
<15.5 MeV
0
1/2
ντ
tau neutrino
91.2 GeV
0
1
Z0
weak force
Leptons
0.511 MeV
-1
1/2
e
electron
105.7 MeV
-1
1/2
μ
muon
1.777 GeV
-1
1/2
τ
tau
80.4 GeV
±1
1
W±
weak force
Bosons (Forces)


Particle Hierarchy
Matter
Diminishing Scale
Molecules
Atoms
Nucleus with Electrons
Sub-Atomic Particles
Protons and Neutrons
Nucleons
Fermions
Leptons
Quarks
Bosons
Gluons
Muons
and many others
Elementary Particles


FERMIONS*
BOSONS
First Generation
Second Generation
Third Generation
Mass (giga-electron-volts)
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-10}
10^{-11}
10^{-12}
Top quark
Higgs
Z
W
Bottom quark
Charm quark
Tau
Strange quark
Muon
Down quark
Up quark
Electron
MASSLESS BOSONS
Photon
Gluon
Muon-neutrino
Tau-neutrino
Electron-neutrino

număr asociat sarcinii electrice (Q)

număr barionic B

număr leptonic L (L_e, L_μ, L_τ)

	Gravity	Weak	Electromagnetic	Strong
		(Electroweak)		
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

interacție slabă (cuarcii și leptonii)

interacție tare (cuarcii)

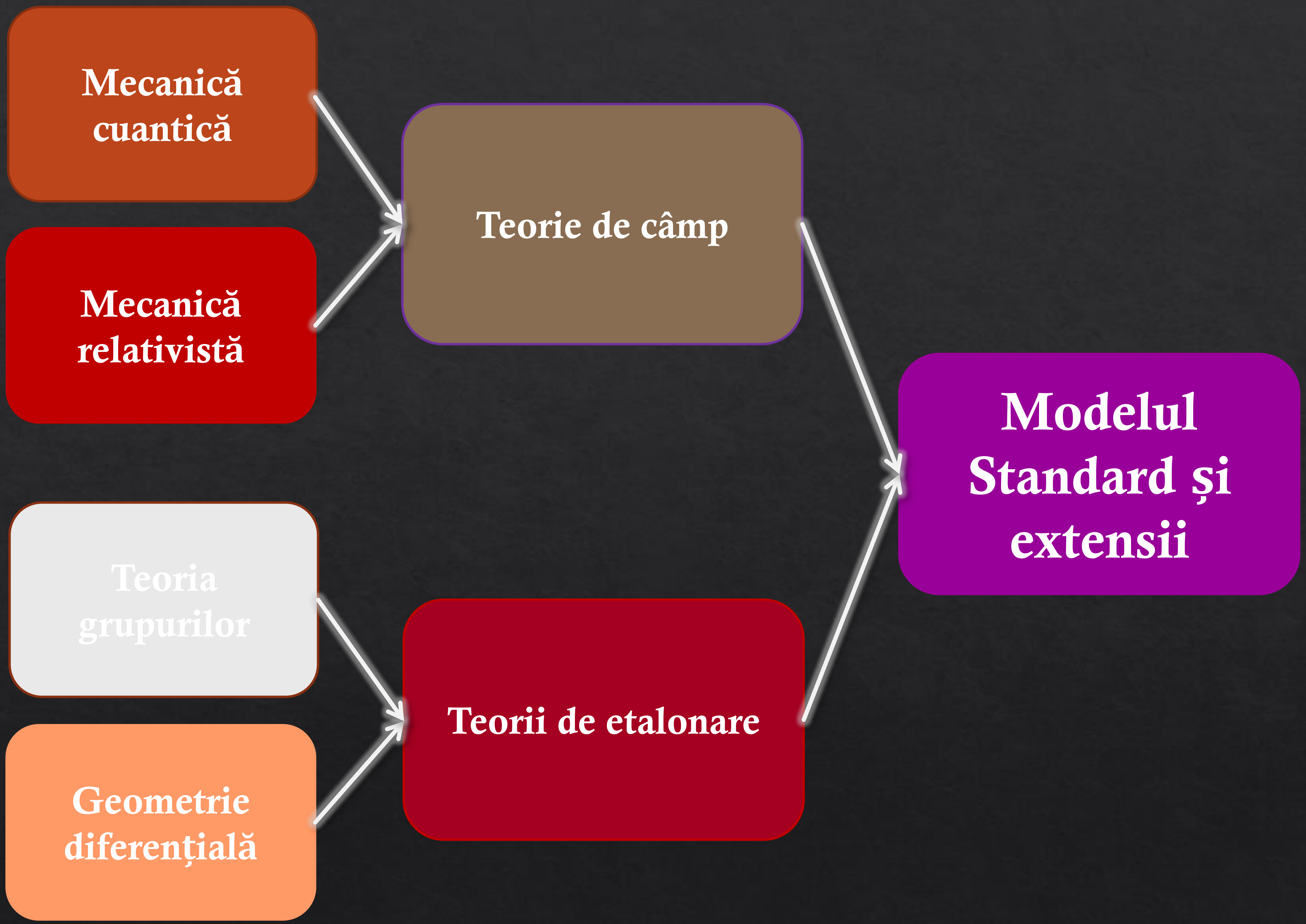
interacție electromagnetică (particule cu sarcină electrică: cuarci, leptoni cu sarcină electrică) indiscernabilitatea particulelor identice

statistică cuantică

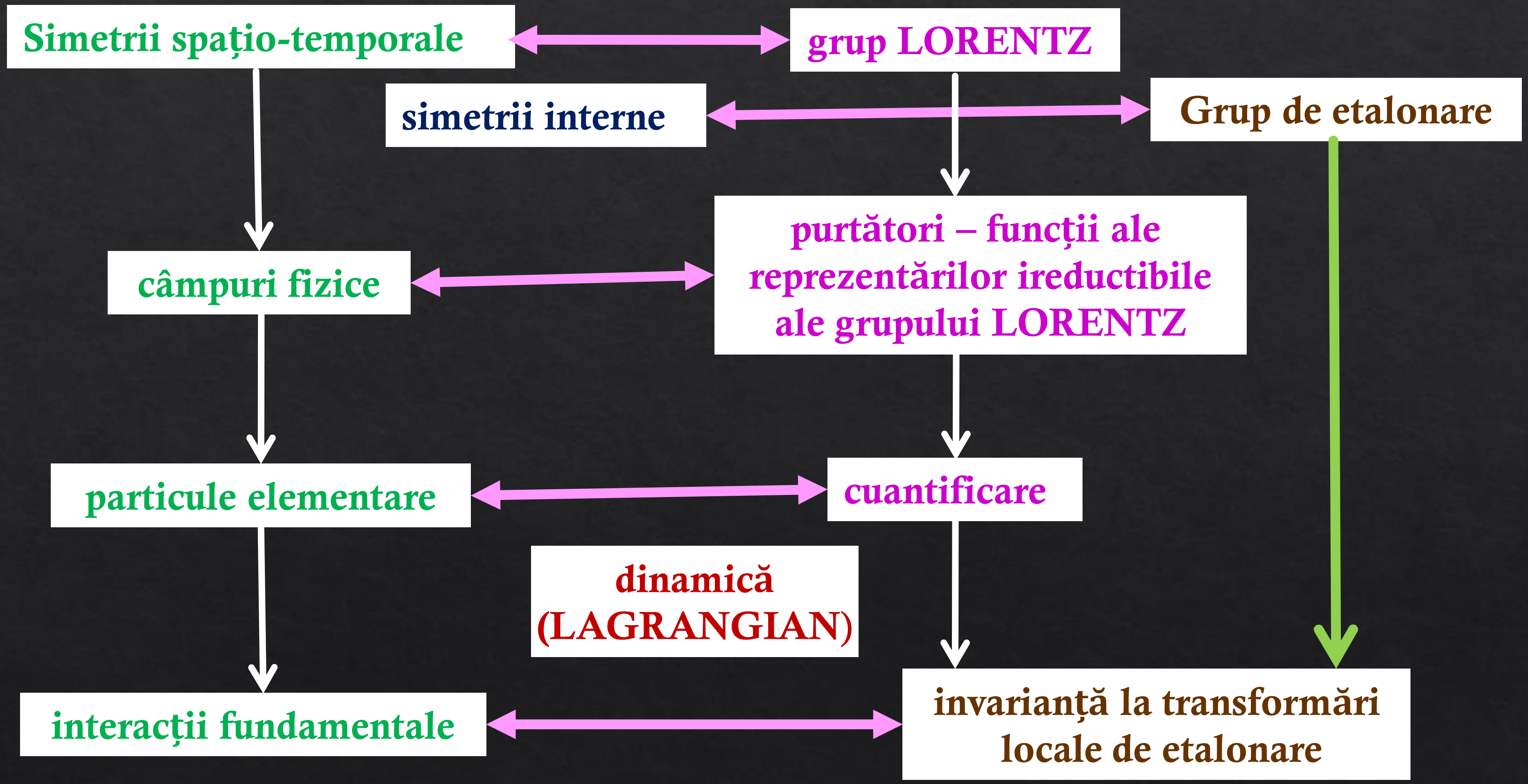
existența antiparticulelor

procese de creare și anihilare a particulelor

interacție cu schimb de particule


Mecanică cuantică
Mecanică relativistă
Teoria grupurilor
Geometrie diferențială
Teorie de câmp
Teorii de etalonare
Modelul Standard și extensii

Schemă teoretică: de la simetrii spațio-temporale la particule elementare și interacții



Lagrangian – Glashow-Weinberg-Salam (interacţie electro-slabă)

$$\mathcal{L}_{GWS} = \sum_f (\bar{\Psi}_f (i\gamma^\mu \partial\mu - m_f)\Psi_f - eQ_f \bar{\Psi}_f \gamma^\mu \Psi_f A_\mu) +$$

$$+ \frac{g}{\sqrt{2}} \sum_i (\bar{a}^i_L \gamma^\mu b^i_L W^+_\mu + \bar{b}^i_L \gamma^\mu a^i_L W^-_\mu) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I^3_f - 2s^2_w Q_f - I^3_f \gamma_5)\Psi_f Z_\mu +$$

$$- \frac{1}{4} |\partial_\mu A_\nu - \partial_\nu A_\mu - ie(W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 - \frac{1}{2} |\partial_\mu W^+_\nu - \partial_\nu W^+_\mu +$$

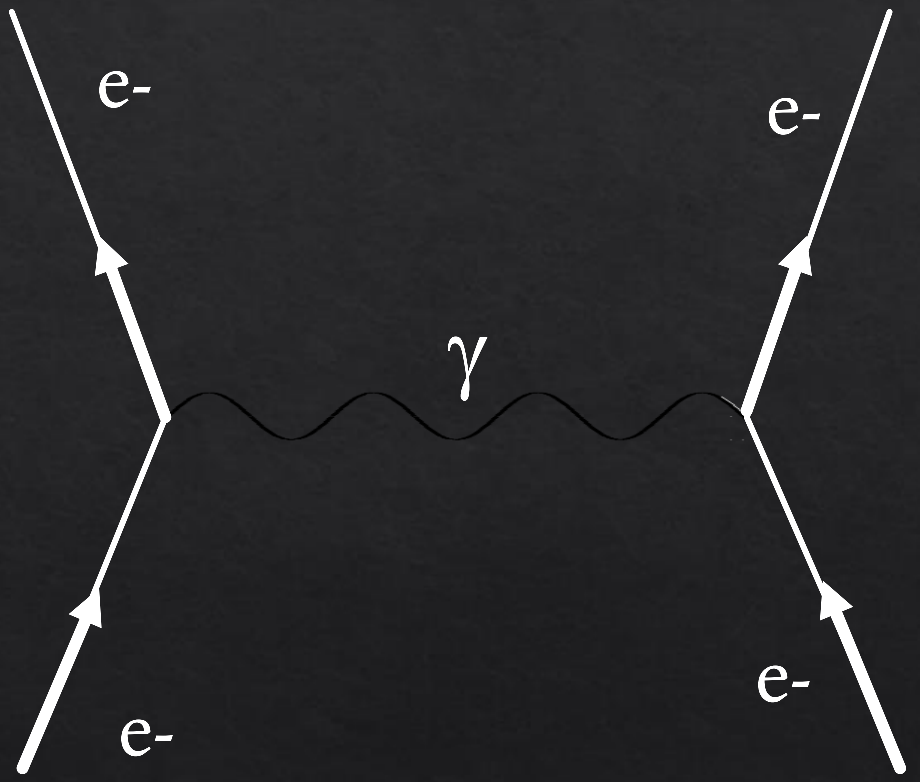
$$- ie(W^+_\mu A_\nu - W^+_\nu A_\mu) + ig' c_w (W^+_\mu Z_\nu - W^+_\nu Z_\mu|^2 +$$

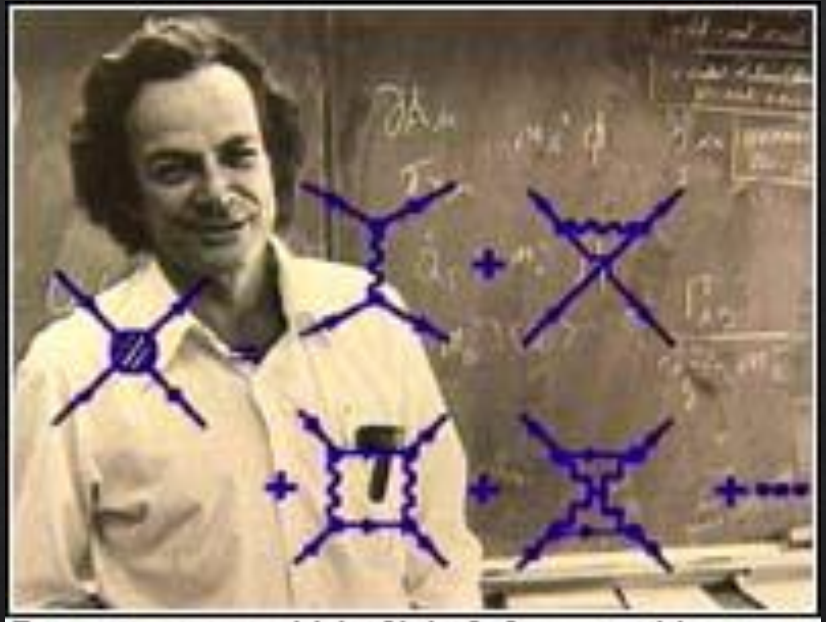
$$- \frac{1}{4} |\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W^-_\mu W^+_\nu - W^+_\mu W^-_\nu)|^2 +$$

$$- \frac{1}{2} M^2_\eta \eta^2 - \frac{g M^2_\eta}{8M_W} \eta^3 - \frac{g'^2 M^2_\eta}{32 M_W} \eta^4 + |M_W W^+_\mu + \frac{g}{2} \eta W^+_\mu|^2 +$$

$$+ \frac{1}{2} |\partial_\mu \eta + i M_Z Z_\mu + \frac{ig}{2c_w} \eta Z_\mu|^2 - \sum_f \frac{g}{2} \frac{m_f}{M_W} \bar{\Psi}_f \Psi_f \eta$$

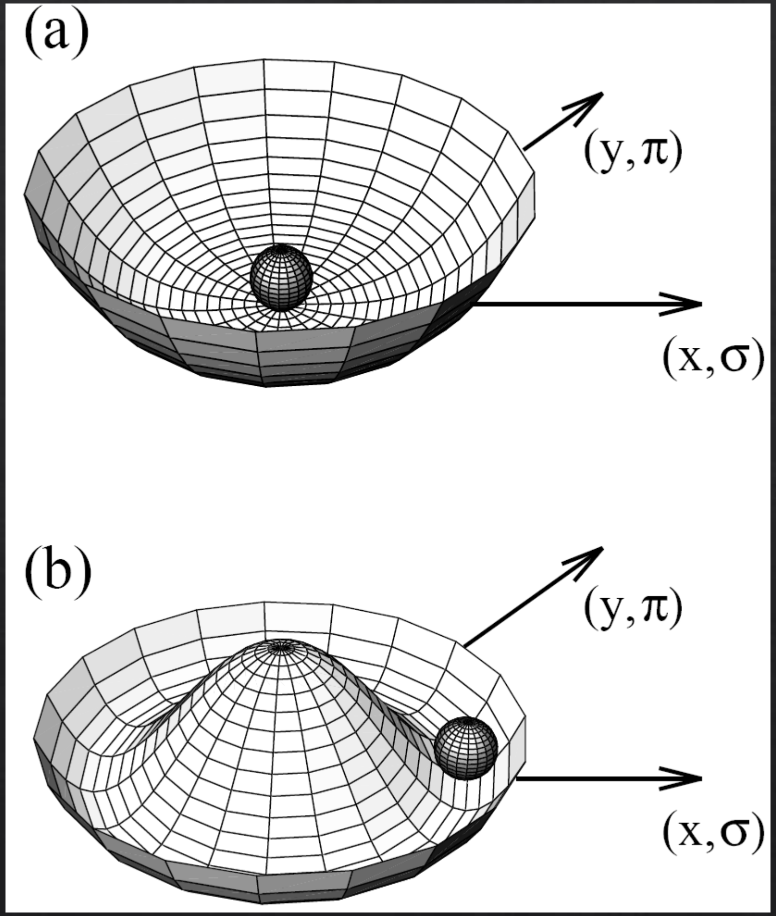
Feynman – diagrame și reguli





Feynman earned his Nobel for creating these diagrams
(Courtesy Auckland University)

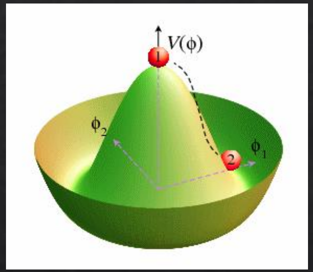
De unde apare masa particulelor în teorie?



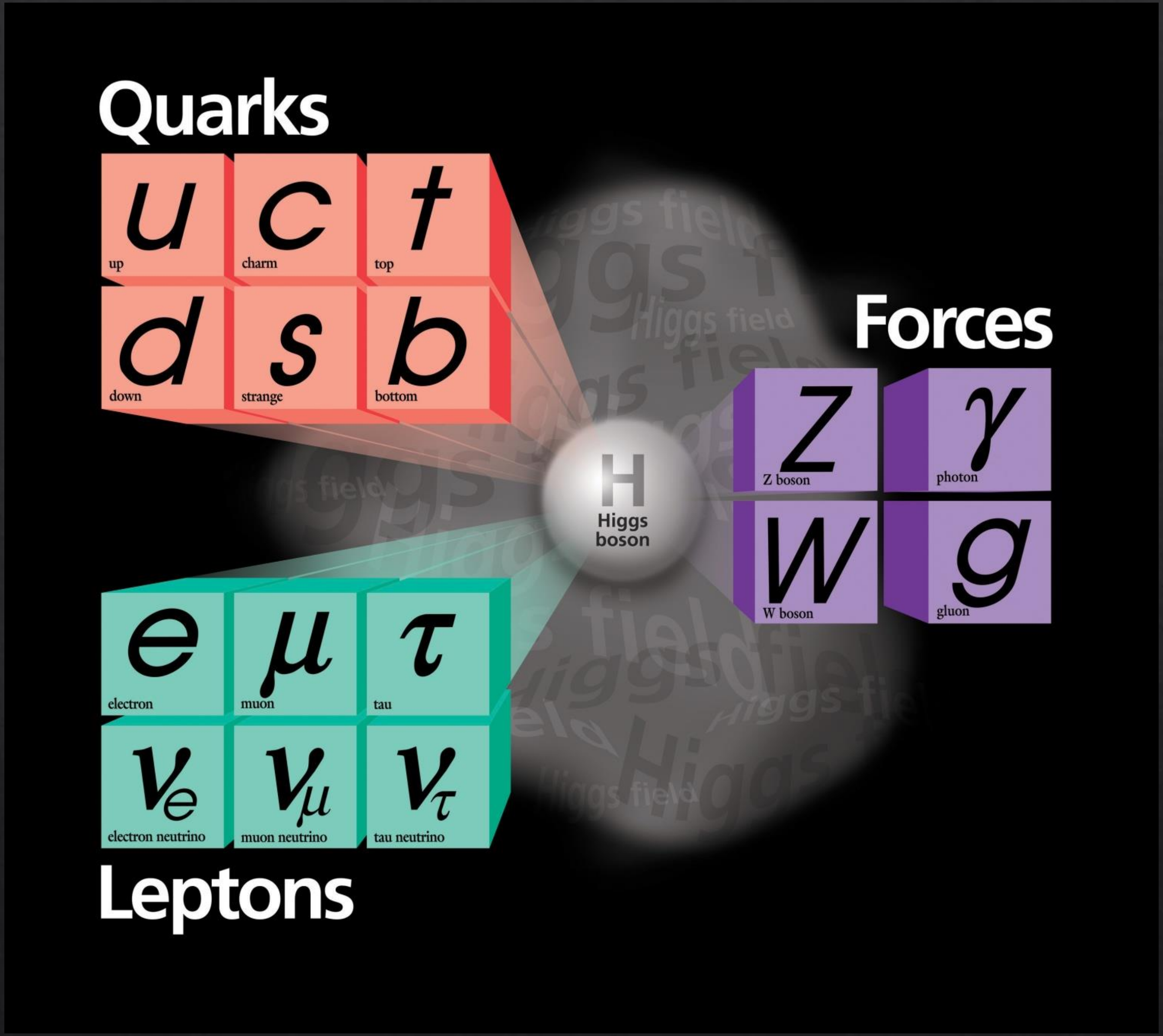
W^+, W^-, Z – au masă

- rezultă bozonul Higgs

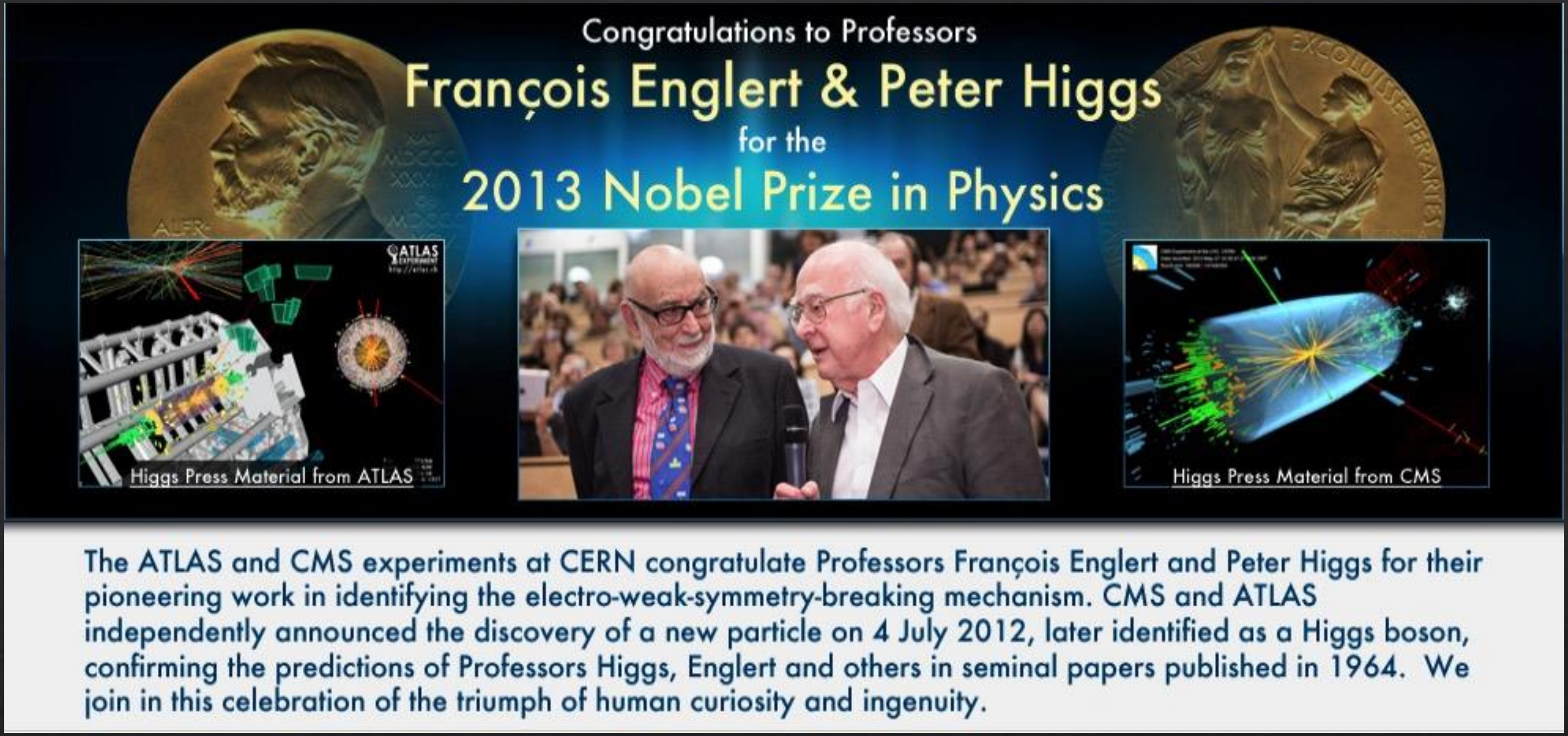
fără rupere spontană de simetrie



rupere spontană de simetrie

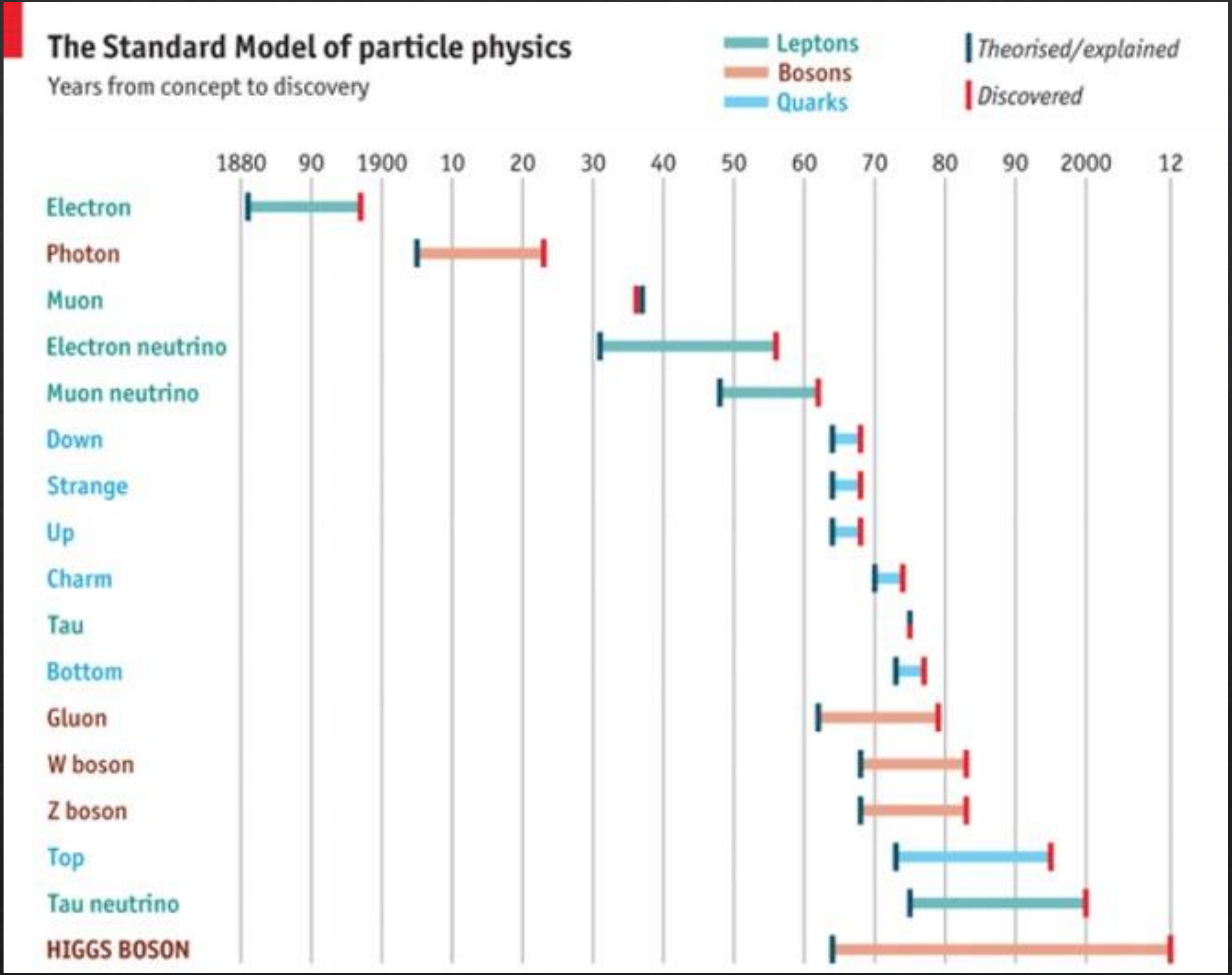


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
H
Higgs boson
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons
Higgs field

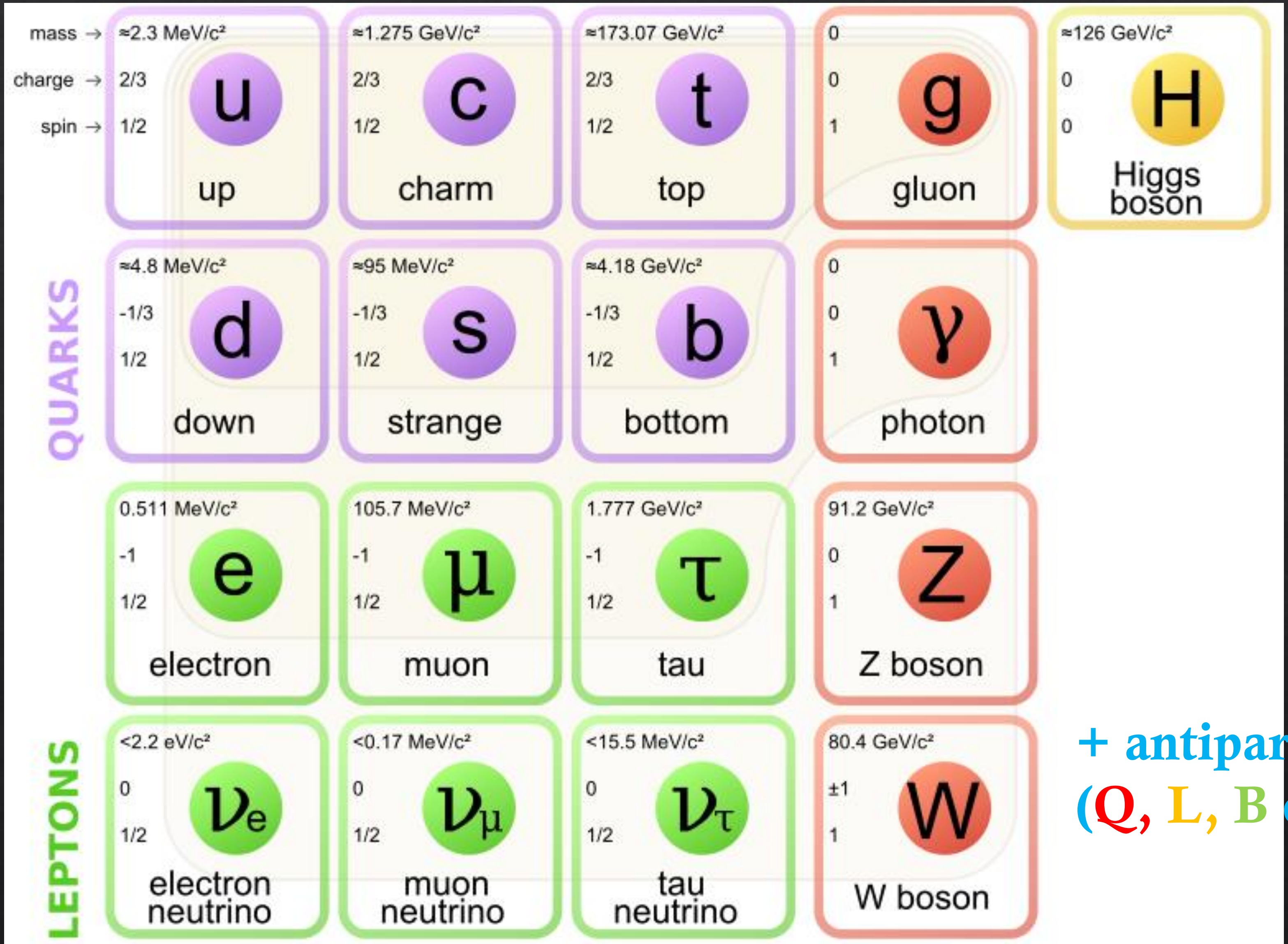


Higgs boson discovery was the culmination of the decades of dedicated and intense work by so many collaborators in designing, building and operating ATLAS, and in understanding and analysing the data. None of it would have been possible without the huge dedication also of the LHC accelerator team, the worldwide distributed computing teams, and the continuing support of the governments and funding agencies of the 38 countries home to our 177 member institutes.

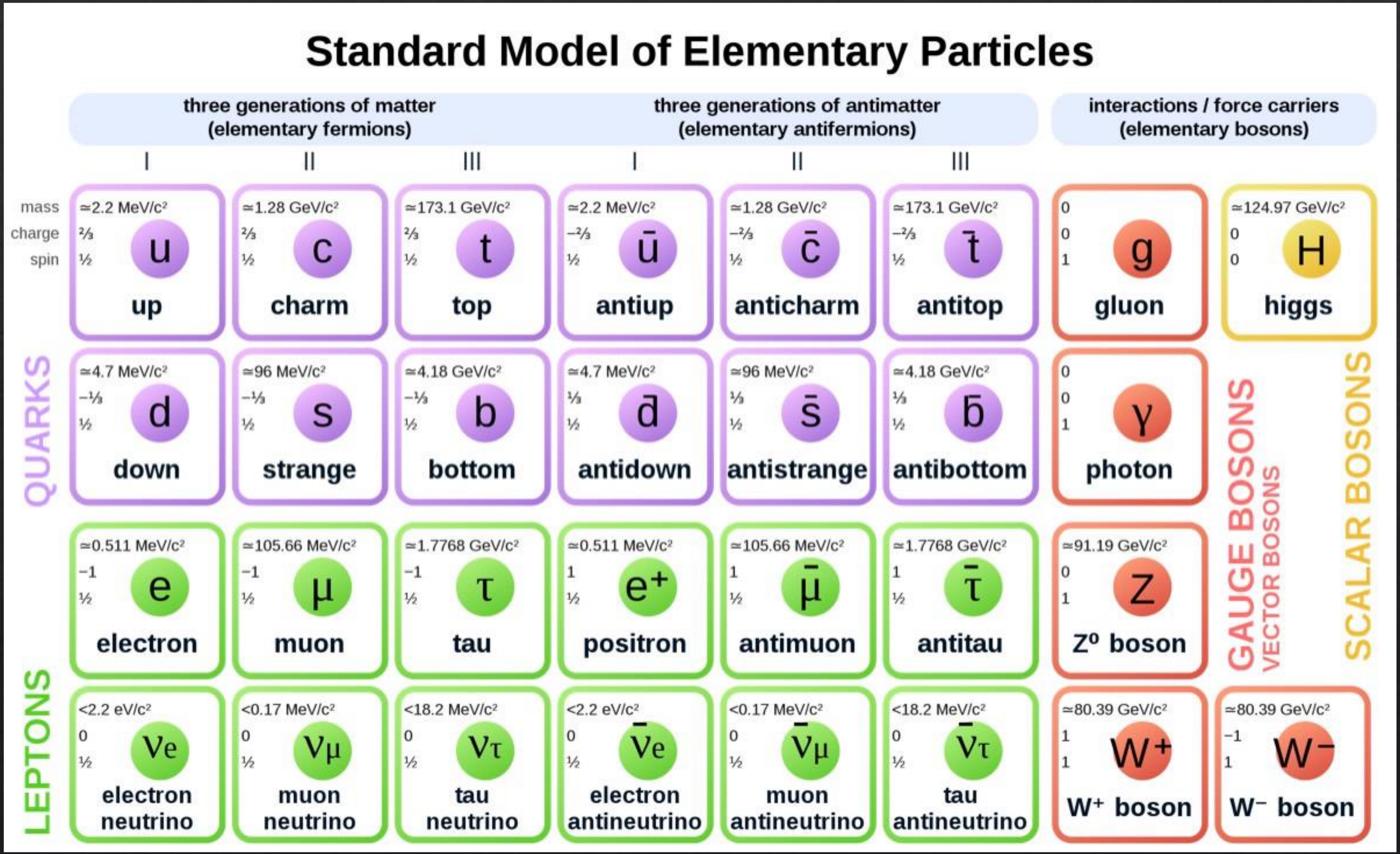
We can all feel proud that our experimental observations demonstrated that the insights rewarded by the Nobel prize are realised in nature.


The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880
90
1900
10
20
30
40
50
60
70
80
90
2000
12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON

Modelul Standard

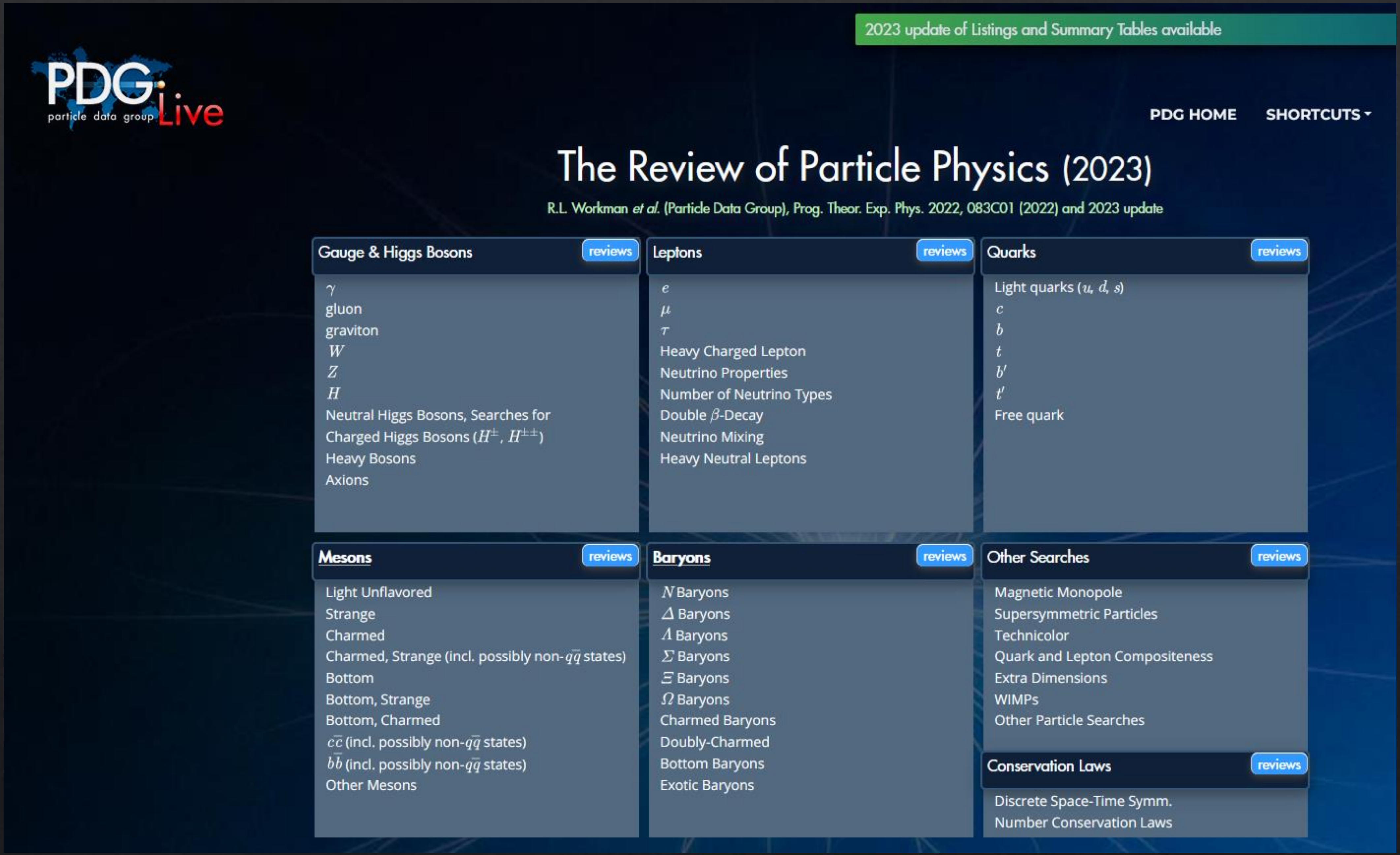


+ antiparticule
(Q, L, B opus)!


Standard Model of Elementary Particles
three generations of matter (elementary fermions)
three generations of antimatter (elementary antifermions)
interactions / force carriers (elementary bosons)
I
II
III
I
II
III
mass
charge
spin
QUARKS
LEPTONS
≃2.2 MeV/c² ⅔ ½ u up
≃1.28 GeV/c² ⅔ ½ c charm
≃173.1 GeV/c² ⅔ ½ t top
≃2.2 MeV/c² −⅔ ½ ū antiup
≃1.28 GeV/c² −⅔ ½ c̄ anticharm
≃173.1 GeV/c² −⅔ ½ t̄ antitop
0 0 1 g gluon
≃124.97 GeV/c² 0 0 H higgs
≃4.7 MeV/c² −⅓ ½ d down
≃96 MeV/c² −⅓ ½ s strange
≃4.18 GeV/c² −⅓ ½ b bottom
≃4.7 MeV/c² ⅓ ½ d̄ antidown
≃96 MeV/c² ⅓ ½ s̄ antistrange
≃4.18 GeV/c² ⅓ ½ b̄ antibottom
0 0 1 γ photon
≃0.511 MeV/c² −1 ½ e electron
≃105.66 MeV/c² −1 ½ μ muon
≃1.7768 GeV/c² −1 ½ τ tau
≃0.511 MeV/c² 1 ½ e⁺ positron
≃105.66 MeV/c² 1 ½ μ̄ antimuon
≃1.7768 GeV/c² 1 ½ τ̄ antitau
≃91.19 GeV/c² 0 1 Z Z⁰ boson
<2.2 eV/c² 0 ½ νe electron neutrino
<0.17 MeV/c² 0 ½ νμ muon neutrino
<18.2 MeV/c² 0 ½ ντ tau neutrino
<2.2 eV/c² 0 ½ ν̄e electron antineutrino
<0.17 MeV/c² 0 ½ ν̄μ muon antineutrino
<18.2 MeV/c² 0 ½ ν̄τ tau antineutrino
≃80.39 GeV/c² 1 1 W⁺ W⁺ boson
≃80.39 GeV/c² −1 1 W⁻ W⁻ boson
GAUGE BOSONS
VECTOR BOSONS
SCALAR BOSONS

Fizica particulelor elementare

1. Care sunt particulele elementare (ce proprietăți au – masă, sarcină electrică, spin, ...)?
2. Cum interacționează? - De unde obținem informații?
3. Cum producem particule elementare?
4. Cum detectăm particule elementare?


2023 update of Listings and Summary Tables available

PDG HOME SHORTCUTS

The Review of Particle Physics (2023)

R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. 2022, 083C01 (2022) and 2023 update

Gauge & Higgs Bosons — reviews
- γ
- gluon
- graviton
- W
- Z
- H
- Neutral Higgs Bosons, Searches for
- Charged Higgs Bosons ($H^{\pm}$, $H^{\pm\pm}$)
- Heavy Bosons
- Axions

Leptons — reviews
- e
- μ
- τ
- Heavy Charged Lepton
- Neutrino Properties
- Number of Neutrino Types
- Double β-Decay
- Neutrino Mixing
- Heavy Neutral Leptons

Quarks — reviews
- Light quarks (u, d, s)
- c
- b
- t
- b'
- t'
- Free quark

Mesons — reviews
- Light Unflavored
- Strange
- Charmed
- Charmed, Strange (incl. possibly non-$q\bar{q}$ states)
- Bottom
- Bottom, Strange
- Bottom, Charmed
- $c\bar{c}$ (incl. possibly non-$q\bar{q}$ states)
- $b\bar{b}$ (incl. possibly non-$q\bar{q}$ states)
- Other Mesons

Baryons — reviews
- N Baryons
- Δ Baryons
- Λ Baryons
- Σ Baryons
- Ξ Baryons
- Ω Baryons
- Charmed Baryons
- Doubly-Charmed
- Bottom Baryons
- Exotic Baryons

Other Searches — reviews
- Magnetic Monopole
- Supersymmetric Particles
- Technicolor
- Quark and Lepton Compositeness
- Extra Dimensions
- WIMPs
- Other Particle Searches

Conservation Laws — reviews
- Discrete Space-Time Symm.
- Number Conservation Laws

https://pdglive.lbl.gov

Quantity	Symbol, equation	Value	Uncertainty (ppb)
speed of light in vacuum	c	$299\,792\,458$ m s^{-1}	exact
Planck constant	h	$6.626\,070\,15\times10^{-34}$ J s (or J/Hz)$^\sharp$	exact
Planck constant, reduced	$\hbar \equiv h/2\pi$	$1.054\,571\,817\ldots\times10^{-34}$ J s	exact*
		$= 6.582\,119\,569\ldots\times10^{-22}$ MeV s	exact*
electron charge magnitude	e	$1.602\,176\,634\times10^{-19}$ C	exact
conversion constant	$\hbar c$	$197.326\,980\,4\ldots$ MeV fm	exact*
conversion constant	$(\hbar c)^2$	$0.389\,379\,372\,1\ldots$ GeV^2 mbarn	exact*
electron mass	m_e	$0.510\,998\,950\,00(15)$ MeV$/c^2$ $= 9.109\,383\,7015(28)\times10^{-31}$ kg	0.30
proton mass	m_p	$938.272\,088\,16(29)$ MeV$/c^2$ $= 1.672\,621\,923\,69(51)\times10^{-27}$ kg	0.31
		$= 1.007\,276\,466\,621(53)$ u $= 1836.152\,673\,43(11)\ m_e$	0.053, 0.060
neutron mass	m_n	$939.565\,420\,52(54)$ MeV$/c^2$ $= 1.008\,664\,915\,95(49)$ u	0.57, 0.48
deuteron mass	m_d	$1875.612\,942\,57(57)$ MeV$/c^2$	0.30
unified atomic mass unit**	$u = (\text{mass }^{12}\text{C atom})/12$	$931.494\,102\,42(28)$ MeV$/c^2$ $= 1.660\,539\,066\,60(50)\times10^{-27}$ kg	0.30
permittivity of free space	$\epsilon_0 = 1/\mu_0 c^2$	$8.854\,187\,8128(13)\times10^{-12}$ F m^{-1}	0.15
permeability of free space	$\mu_0/(4\pi\times10^{-7})$	$1.000\,000\,000\,55(15)$ N A^{-2}	0.15
fine-structure constant	$\alpha = e^2/4\pi\epsilon_0\hbar c$	$7.297\,352\,5693(11)\times10^{-3} = 1/137.035\,999\,084(21)^\dagger$	0.15
classical electron radius	$r_e = e^2/4\pi\epsilon_0 m_e c^2$	$2.817\,940\,3262(13)\times10^{-15}$ m	0.45
(e^- Compton wavelength)$/2\pi$	$\lambda\!\!\!^{-}_e = \hbar/m_e c = r_e\alpha^{-1}$	$3.861\,592\,6796(12)\times10^{-13}$ m	0.30
Bohr radius ($m_{\text{nucleus}} = \infty$)	$a_\infty = 4\pi\epsilon_0\hbar^2/m_e e^2 = r_e\alpha^{-2}$	$0.529\,177\,210\,903(80)\times10^{-10}$ m	0.15
wavelength of 1 eV$/c$ particle	$hc/(1\text{ eV})$	$1.239\,841\,984\ldots\times10^{-6}$ m	exact*
Rydberg energy	$hcR_\infty = m_e e^4/2(4\pi\epsilon_0)^2\hbar^2 = m_e c^2\alpha^2/2$	$13.605\,693\,122\,994(26)$ eV	1.9×10^{-3}
Thomson cross section	$\sigma_T = 8\pi r_e^2/3$	$0.665\,245\,873\,21(60)$ barn	0.91
Bohr magneton	$\mu_B = e\hbar/2m_e$	$5.788\,381\,8060(17)\times10^{-11}$ MeV T^{-1}	0.3
nuclear magneton	$\mu_N = e\hbar/2m_p$	$3.152\,451\,258\,44(96)\times10^{-14}$ MeV T^{-1}	0.31
electron cyclotron freq./field	$\omega^e_{\text{cycl}}/B = e/m_e$	$1.758\,820\,010\,76(53)\times10^{11}$ rad s^{-1} T^{-1}	0.30
proton cyclotron freq./field	$\omega^p_{\text{cycl}}/B = e/m_p$	$9.578\,833\,1560(29)\times10^{7}$ rad s^{-1} T^{-1}	0.31

gravitational constant[‡]	G_N	$6.674\,30(15)\times10^{-11}$ m^3 kg^{-1} s^{-2}	2.2×10^4
		$= 6.708\,83(15)\times10^{-39}\ \hbar c\ (\text{GeV}/c^2)^{-2}$	2.2×10^4
standard gravitational accel.	g_N	$9.806\,65$ m s^{-2}	exact
Avogadro constant	N_A	$6.022\,140\,76\times10^{23}$ mol^{-1}	exact
Boltzmann constant	k	$1.380\,649\times10^{-23}$ J K^{-1}	exact
		$= 8.617\,333\,262\ldots\times10^{-5}$ eV K^{-1}	exact*
molar volume, ideal gas at STP	$N_A k$ (273.15 K)/(101 325 Pa)	$22.413\,969\,54\ldots\times10^{-3}$ m^3 mol^{-1}	exact*
Wien displacement law constant	$b = \lambda_{\max}T$	$2.897\,771\,955\ldots\times10^{-3}$ m K	exact*
Stefan-Boltzmann constant	$\sigma = \pi^2k^4/60\hbar^3c^2$	$5.670\,374\,419\ldots\times10^{-8}$ W m^{-2} K^{-4}	exact*
Fermi coupling constant[‡‡]	$G_F/(\hbar c)^3$	$1.166\,378\,7(6)\times10^{-5}$ GeV^{-2}	510
weak-mixing angle	$\sin^2\widehat{\theta}(M_Z)$ ($\overline{\text{MS}}$)	0.231 22(4)[††]	1.7×10^5
$W^\pm$ boson mass	m_W	80.379(12) GeV/c^2	1.5×10^5
Z^0 boson mass	m_Z	91.1876(21) GeV/c^2	2.3×10^4
strong coupling constant	$\alpha_s(m_Z)$	0.1179(10)	8.5×10^6

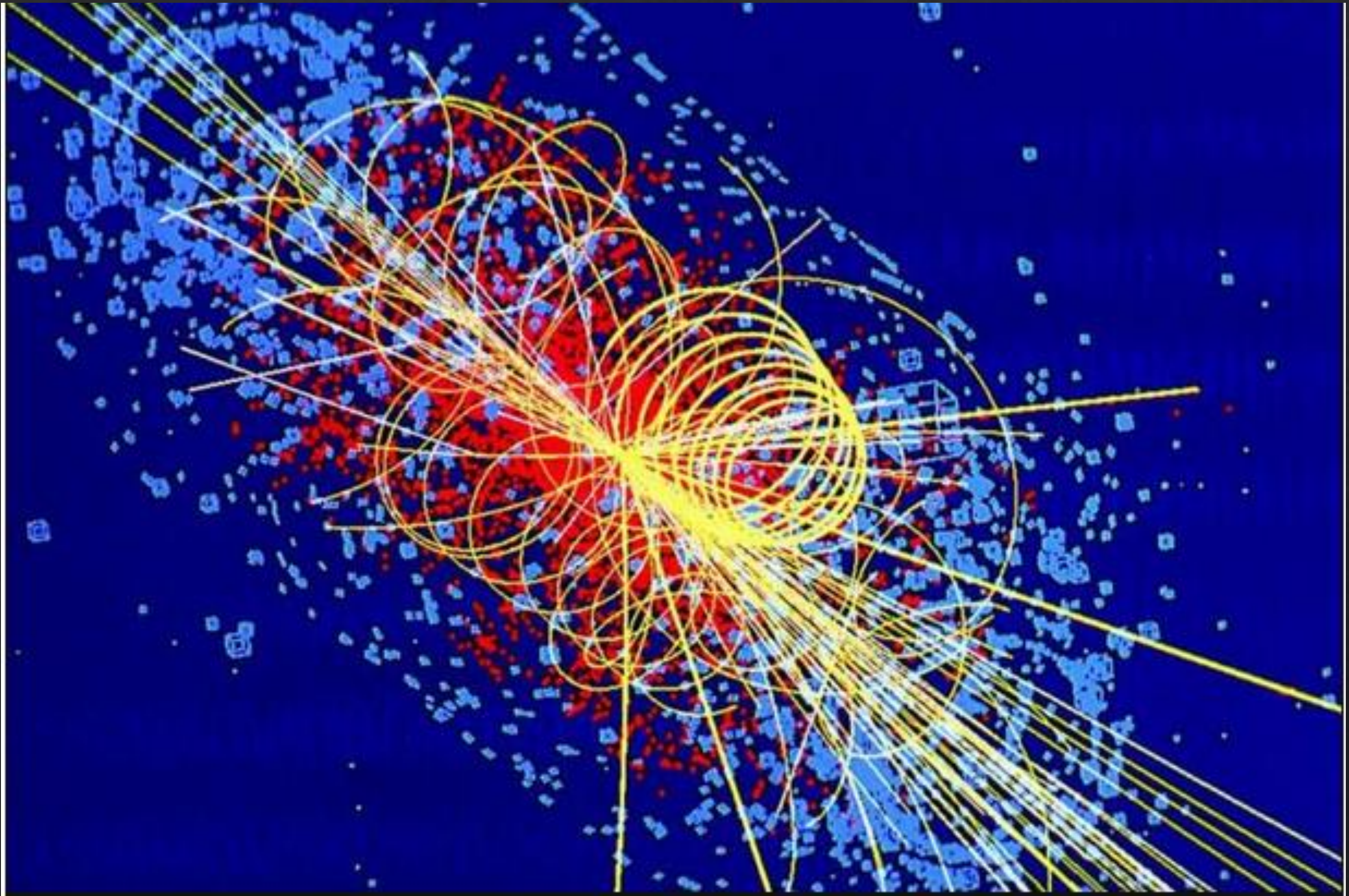
$\pi = 3.141\,592\,653\,589\,793\,238\ldots$ $e = 2.718\,281\,828\,459\,045\,235\ldots$ $\gamma = 0.577\,215\,664\,901\,532\,860\ldots$

1 in $\equiv$ 0.0254 m	1 G $\equiv 10^{-4}$ T	1 eV = $1.602\ 176\ 634\times10^{-19}$ J (exact)	kT at 300 K = $[38.681\ 740(22)]^{-1}$ eV
1 Å $\equiv$ 0.1 nm	1 dyne $\equiv 10^{-5}$ N	(1 kg)c^2 = $5.609\ 588\ 603\ldots\times10^{35}$ eV (exact*)	0 °C $\equiv$ 273.15 K
1 barn $\equiv 10^{-28}$ m^2	1 erg $\equiv 10^{-7}$ J	1 C = $2.997\ 924\ 58\times10^9$ esu	1 atmosphere $\equiv$ 760 Torr $\equiv$ 101 325 Pa

♯ CODATA recommends that the unit be J/Hz to stress that in $h = E/\nu$ the frequency ν is in cycles/sec (Hz), not radians/sec.
* These are calculated from exact values and are exact to the number of places given (*i.e.* no rounding).
** The molar mass of ^{12}C is 11.999 999 9958(36) g.
† At $Q^2 = 0$. At $Q^2 \approx m_W^2$ the value is $\sim 1/128$.
‡ Absolute laboratory measurements of G_N have been made only on scales of about 1 cm to 1 m.
‡‡ See the discussion in Sec. 10, "Electroweak model and constraints on new physics."
†† The corresponding $\sin^2\theta$ for the effective angle is 0.23155(4).

2. De unde obținem informații despre particule?

- **ciocniri**
- **dezintegrări**
- **stări legate**



Simulation of a particle collision in which a Higgs boson is produced (Image: Lucas Taylor/CMS)

particle physics collisions: cross section σ_{fi} $= \frac{W_{fi}}{(initial\ \ flux)}(number\ of\ \ final\ states)$
ciocniri: secţiune eficace de împrăştiere

$$d\sigma = \frac{|M|^2}{F}\, dQ$$

M – amplitudine de tranziţie

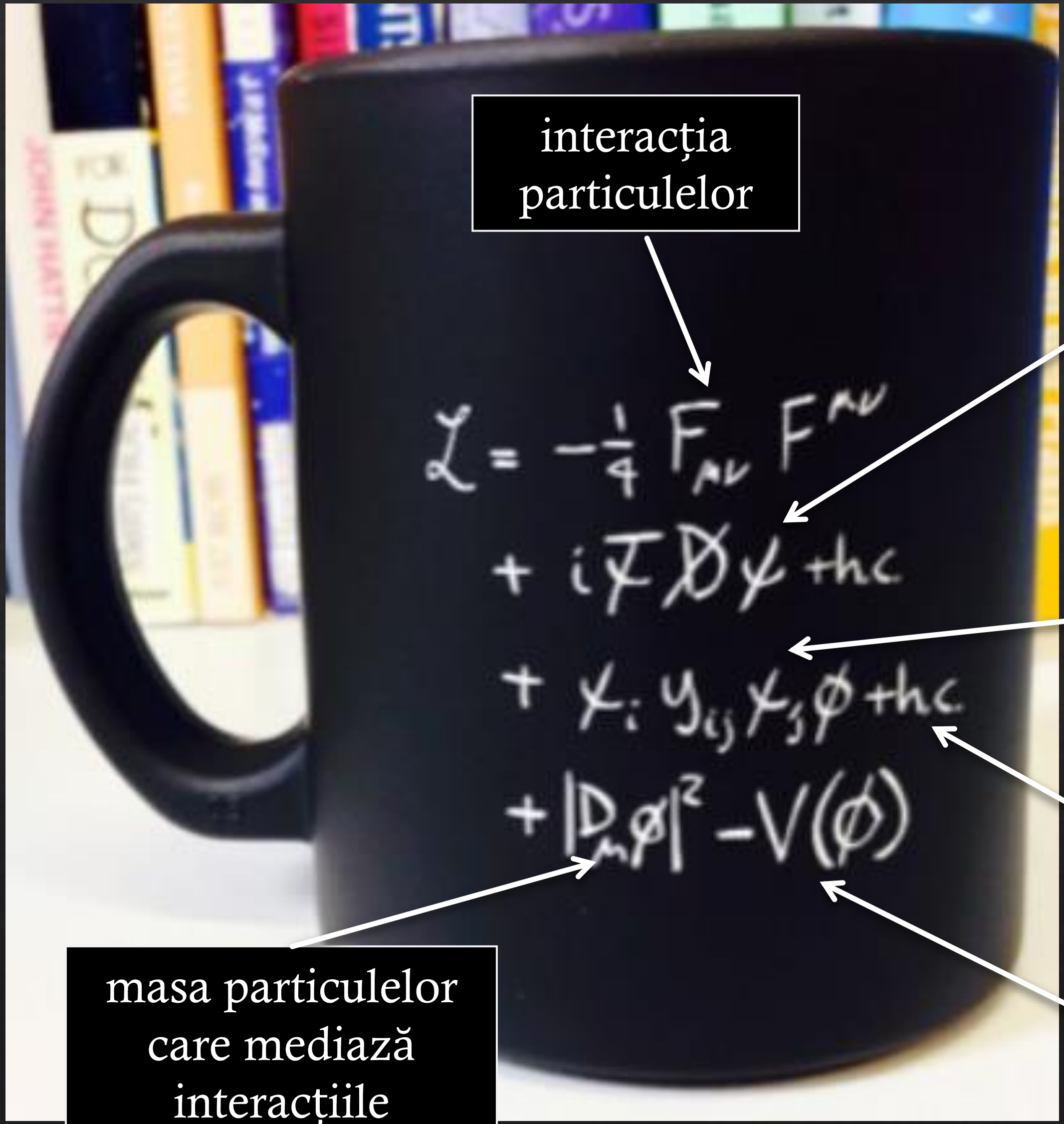
$$\sigma_{tot}(a_1 + a_2 \to b'_1 + \cdots + b'_m) = \frac{1}{2w(s, m_1^2, m_2^2)} \cdot \int \prod_{i=1}^{m} \left(\frac{dp'_i}{(2\pi)^3} \delta_+(p_i'^2 - m_i'^2) \right) (2\pi)^4 \delta(p'_1 + \cdots + p'_m - p_1 - p_2) \cdot |\langle b_1(p'_1) \ldots b_m(p'_m)| \mathbf{T} | a_1(p_1) a_2(p_2) \rangle|^2.$$

dezintegrări: rata de dezintegrare

$$d\Gamma(a(p) \to b_1(p'_1) + \cdots + b_m(p'_m)) = \frac{1}{2m_a}(2\pi)^4 \delta(p'_1 + \cdots + p'_m - p) \cdot \prod_{i=1}^{m} \frac{d^3 p'_i}{(2\pi)^3 2p_i'^0} |\langle b_1(p'_1) \ldots b_m(p'_m)| \mathbf{T} | a(p) \rangle|^2.$$

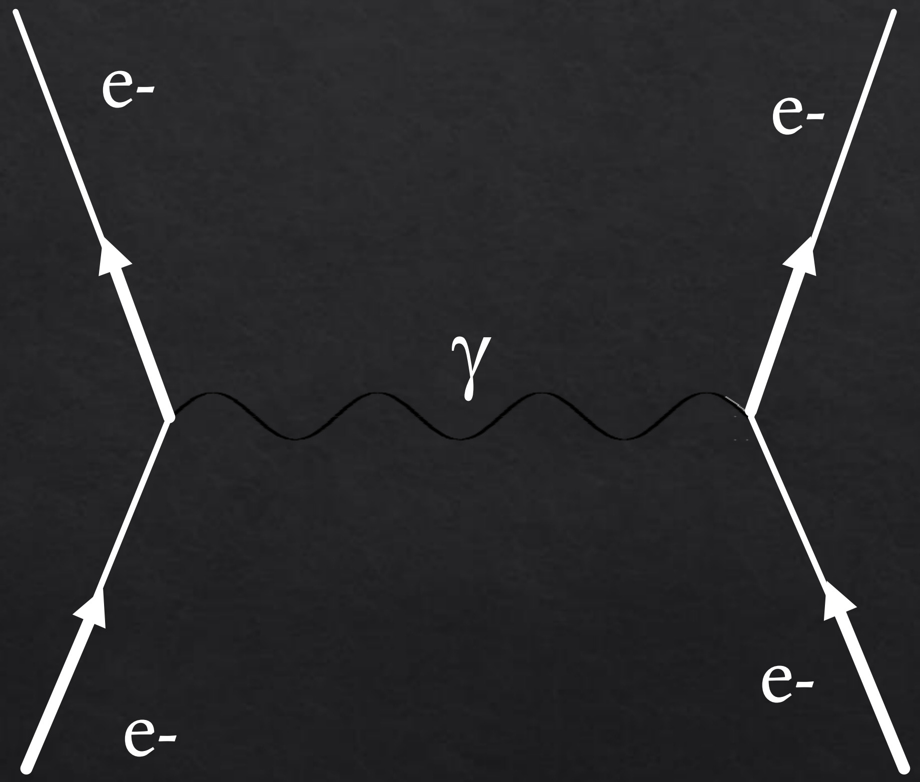
Cum interacționează?

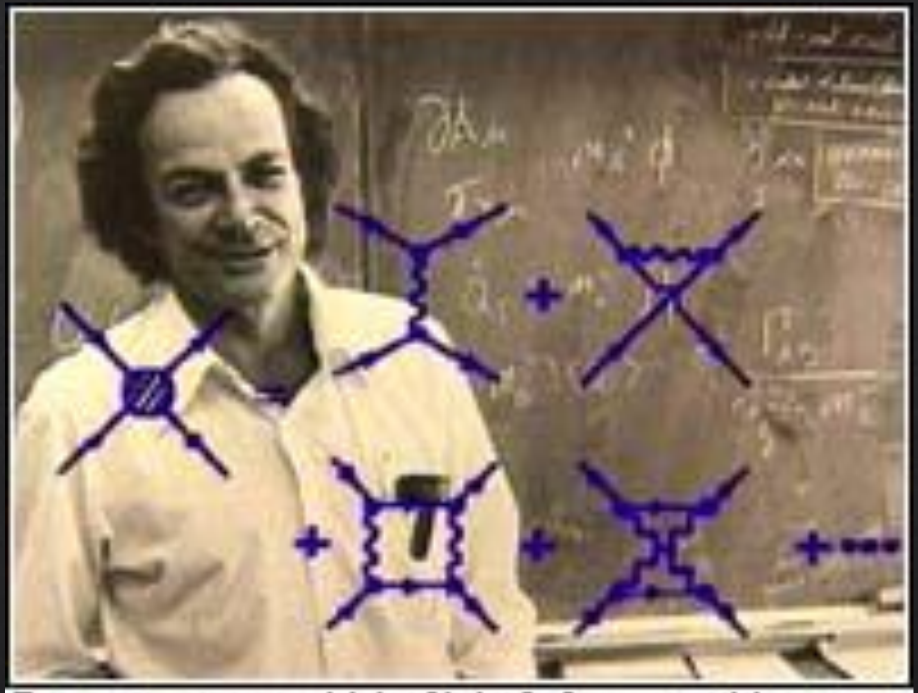
$$
\begin{gathered}
-\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \\
\tfrac{1}{2}ig_s^2(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H - \\
\tfrac{1}{2}m_h^2 H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu\phi^0\partial_\mu\phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} + \\
\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
W^-_\nu\partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - \\
W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)] - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \\
\tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + \\
g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] - \\
\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2] - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \tfrac{1}{2}ig[W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - \\
W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W^-_\mu(H\partial_\mu\phi^+ - \\
\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + \\
igs_w MA_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + \\
igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \\
\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m_u^\lambda)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + \\
m_d^\lambda)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda\gamma e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma d^\lambda_j)] + \tfrac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \\
\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u^\lambda_j) + \\
(\bar{d}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d^\lambda_j)] + \tfrac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)e^\lambda) + (\bar{u}^\lambda_j\gamma^\mu(1 + \\
\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \tfrac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \gamma^5)u^\lambda_j)] + \\
\tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1 + \gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) + \\
i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}^\lambda_j C_{\lambda\kappa}(1 - \gamma^5)d^\kappa_j) + m_u^\lambda(\bar{u}^\lambda_j C_{\lambda\kappa}(1 + \\
\gamma^5)d^\kappa_j] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 + \gamma^5)u^\kappa_j) - m_u^\kappa(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \gamma^5)u^\kappa_j] - \\
\tfrac{g}{2}\tfrac{m_u^\lambda}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + \\
igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + \\
igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + \\
igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) - \\
\tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ - \\
\bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igMs_w[\bar{X}^0 X^-\phi^+ - \\
\bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]
\end{gathered}
$$



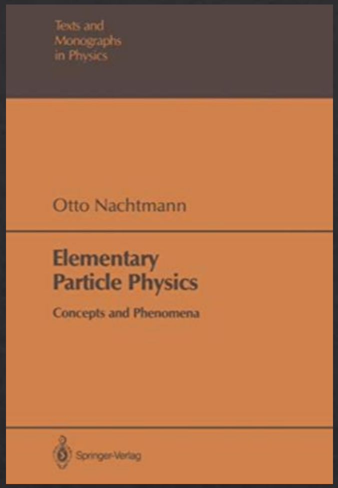
https://home.cern/news/news/cern/sit-down-coffee-standard-model

Feynman – diagrame și reguli





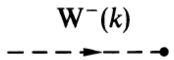
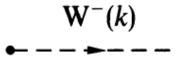
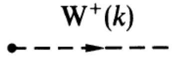
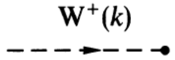
Feynman earned his Nobel for creating these diagrams
(Courtesy Auckland University)

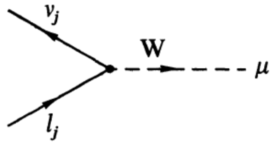
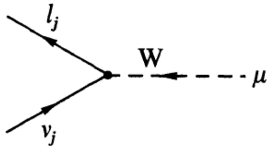
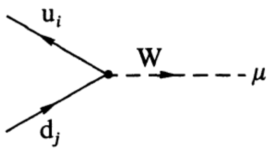
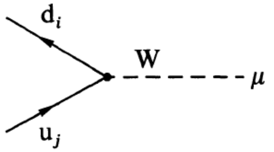


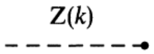
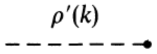
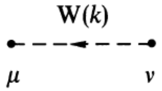
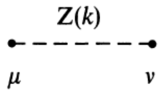
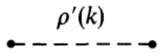
Feynman – diagrame și reguli
Electrodinamică cuantică

electron in initial state	$u(p)$	incoming electron line	$e^-(p)$ 
electron in final state	$\bar{u}(p)$	outgoing electron line	$e^-(p)$ 
positron in initial state	$\bar{v}(q)$	outgoing electron line	$e^+(q)$ 
positron in final state	$v(q)$	incoming electron line	$e^+(q)$ 
photon in initial state	ε^μ	incoming photon line	$\gamma(k)$ 
photon in final state	$\varepsilon^{\mu *}$	outgoing photon line	$\gamma(k)$ 
virtual photon	$\frac{-\mathrm{i} g_{\mu\nu}}{k^2 + \mathrm{i}\varepsilon}$	internal photon line	k  μ ν
virtual electron	$\mathrm{i}\frac{\not{p} + m}{p^2 - m^2 + \mathrm{i}\varepsilon}$	internal electron line	p 
elementary process	$\mathrm{i}e\gamma^\mu$	vertex	

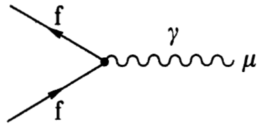
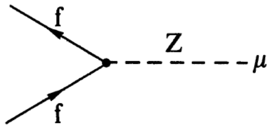
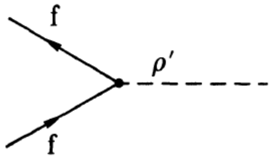
Feynman – diagrame și reguli

W^- initial state	incoming W line	
$\varepsilon(k)$		
W^- in final state	outgoing W line	
$\varepsilon^*(k)$		
W^+ in initial state	outgoing W line	
$\varepsilon(k)$		
W^+ in final state	incoming W line	
$\varepsilon^*(k)$		

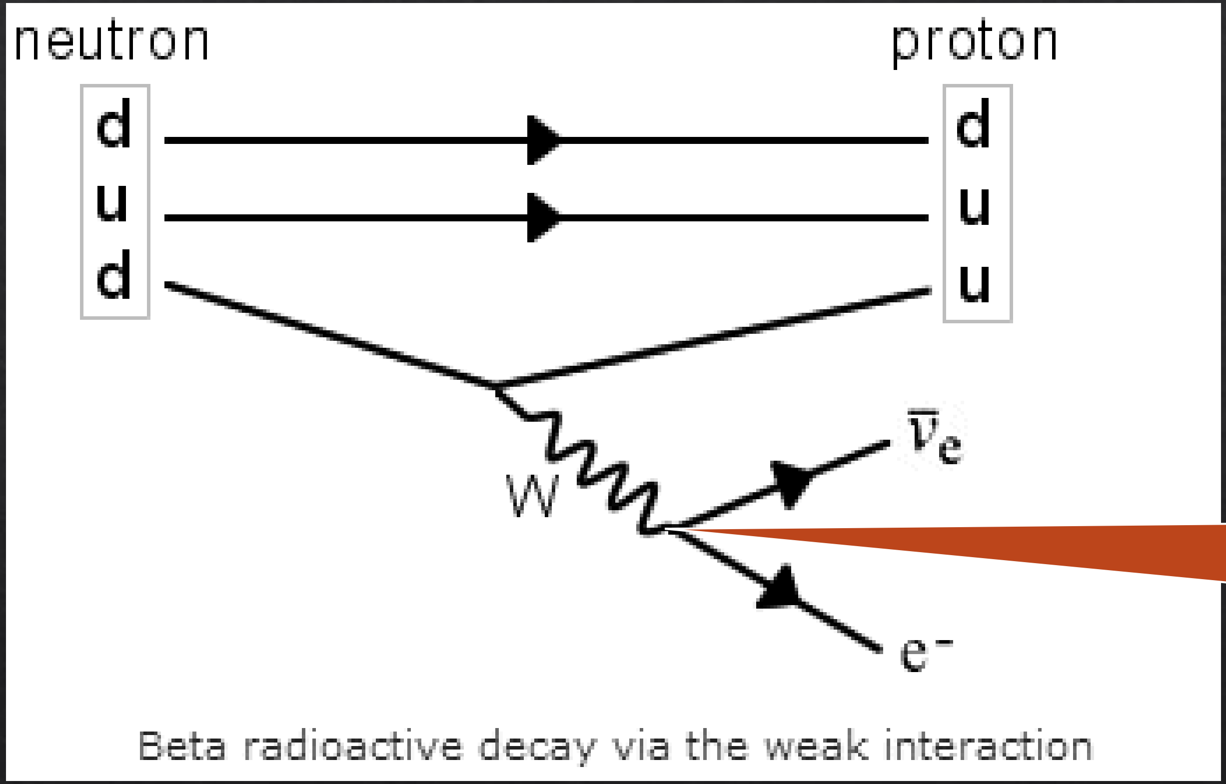
$-i\frac{e}{\sqrt{2}\sin\vartheta_W}\gamma^\mu\frac{1-\gamma_5}{2}$	
$-i\frac{e}{\sqrt{2}\sin\vartheta_W}\gamma^\mu\frac{1-\gamma_5}{2}$	
$-i\frac{e}{\sqrt{2}\sin\vartheta_W}V_{ij}\,\gamma^\mu\frac{1-\gamma_5}{2}$	
$-i\frac{e}{\sqrt{2}\sin\vartheta_W}V_{ji}^*\,\gamma^\mu\frac{1-\gamma_5}{2}$	

Z in initial (final) state	external Z line	
$\varepsilon(k)(\varepsilon^*(k))$		
Higgs particle in initial (final) state	external ρ' line	
1		
virtual W boson	internal W line	
$\frac{i\left(-g^{\mu\nu}+\frac{k^\mu k^\nu}{m_W^2}\right)}{k^2-m_W^2+i\varepsilon}$		
virtual Z boson	internal Z line	
$\frac{i\left(-g^{\mu\nu}+\frac{k^\mu k^\nu}{m_Z^2}\right)}{k^2-m_Z^2+i\varepsilon}$		
virtual Higgs particle	internal ρ' line	
$\frac{i}{k^2-m_{\rho'}^2+i\varepsilon}$		

Fermion–Boson vertices:

$-ieQ_f\gamma^\mu$	
$-i\frac{e}{\sin\vartheta_W\cos\vartheta_W}\left\{T_3^f\gamma^\mu\frac{1-\gamma_5}{2}-\sin^2\vartheta_W Q_f\gamma^\mu\right\}$	
$-i\frac{m_f}{\rho_0}$	

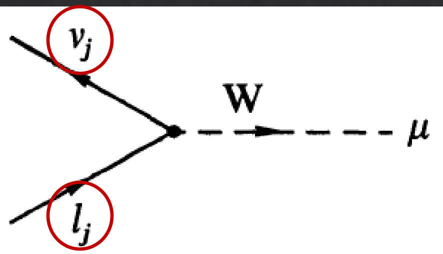
Feynman – diagrame și reguli



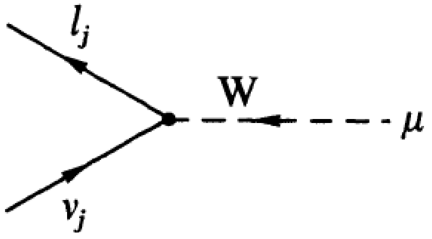
Sarcina electrică se conservă la fiecare vertex

Feynman – diagrame și reguli

$$-\mathrm{i}\frac{e}{\sqrt{2}\sin\vartheta_W}\gamma^\mu\frac{1-\gamma_5}{2}$$



$$-\mathrm{i}\frac{e}{\sqrt{2}\sin\vartheta_W}\gamma^\mu\frac{1-\gamma_5}{2}$$



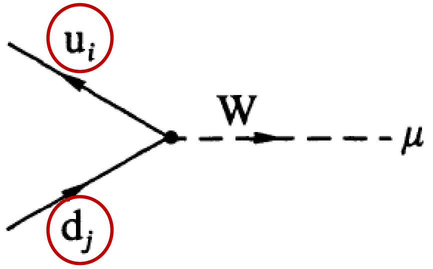
$\nu_1 \equiv \nu_e$, $\nu_2 \equiv \nu_\mu$, $\nu_3 \equiv \nu_\tau$;

$\ell_1 \equiv \mathrm{e}$, $\ell_2 \equiv \mu$, $\ell_3 \equiv \tau$;

$\mathrm{u}_1 \equiv \mathrm{u}$, $\mathrm{u}_2 \equiv \mathrm{c}$, $\mathrm{u}_3 \equiv \mathrm{t}$;

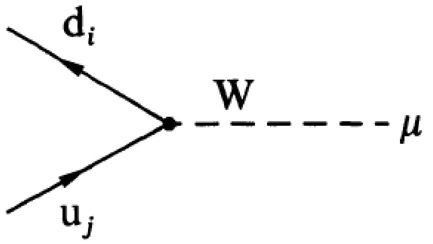
$\mathrm{d}_1 \equiv \mathrm{d}$, $\mathrm{d}_2 \equiv \mathrm{s}$, $\mathrm{d}_3 \equiv \mathrm{b}$.

$$-\mathrm{i}\frac{e}{\sqrt{2}\sin\vartheta_W}V_{ij}\gamma^\mu\frac{1-\gamma_5}{2}$$

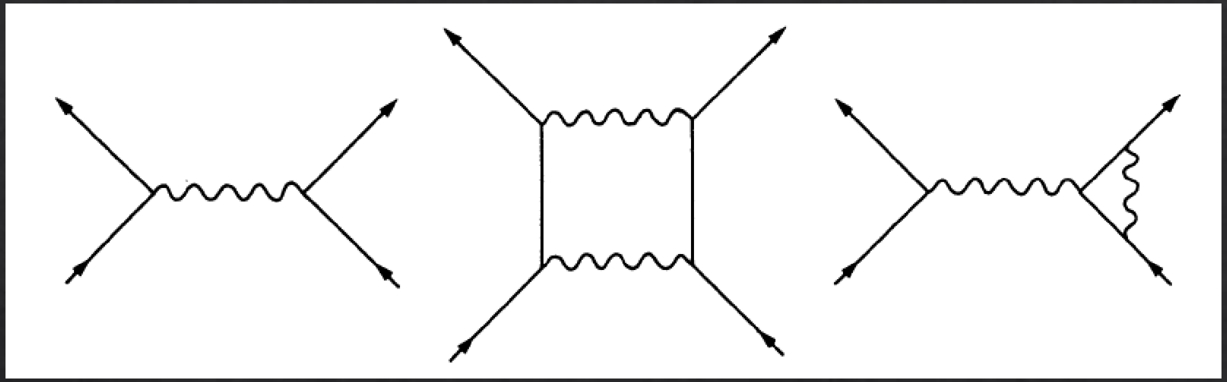


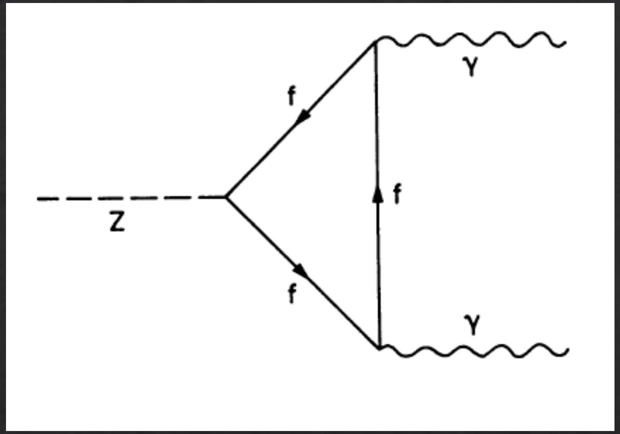
matricea de mixing a cuarcilor
(Cabibbo–Kobayashi–Maskawa)

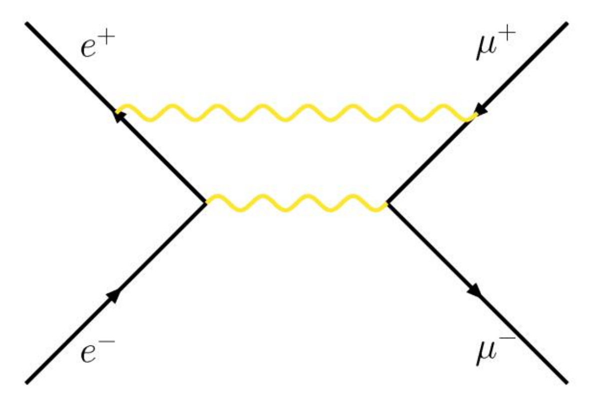
$$-\mathrm{i}\frac{e}{\sqrt{2}\sin\vartheta_W}V_{ji}^*\gamma^\mu\frac{1-\gamma_5}{2}$$

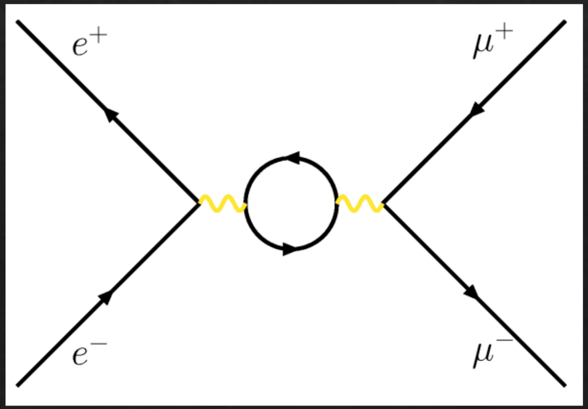


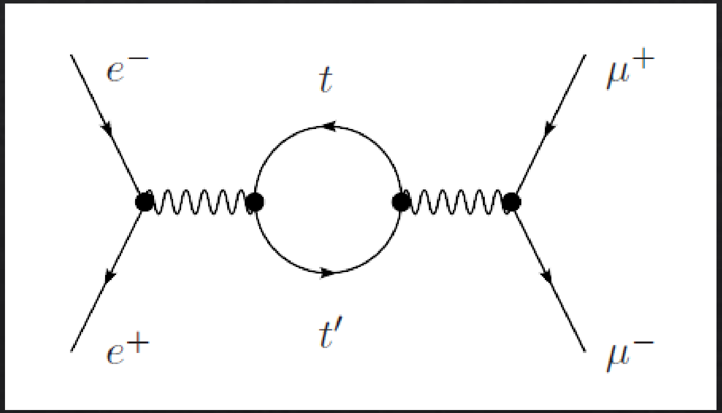
…și mai multe!
Teoria perturbațiilor – corecții



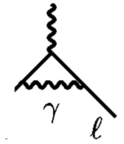




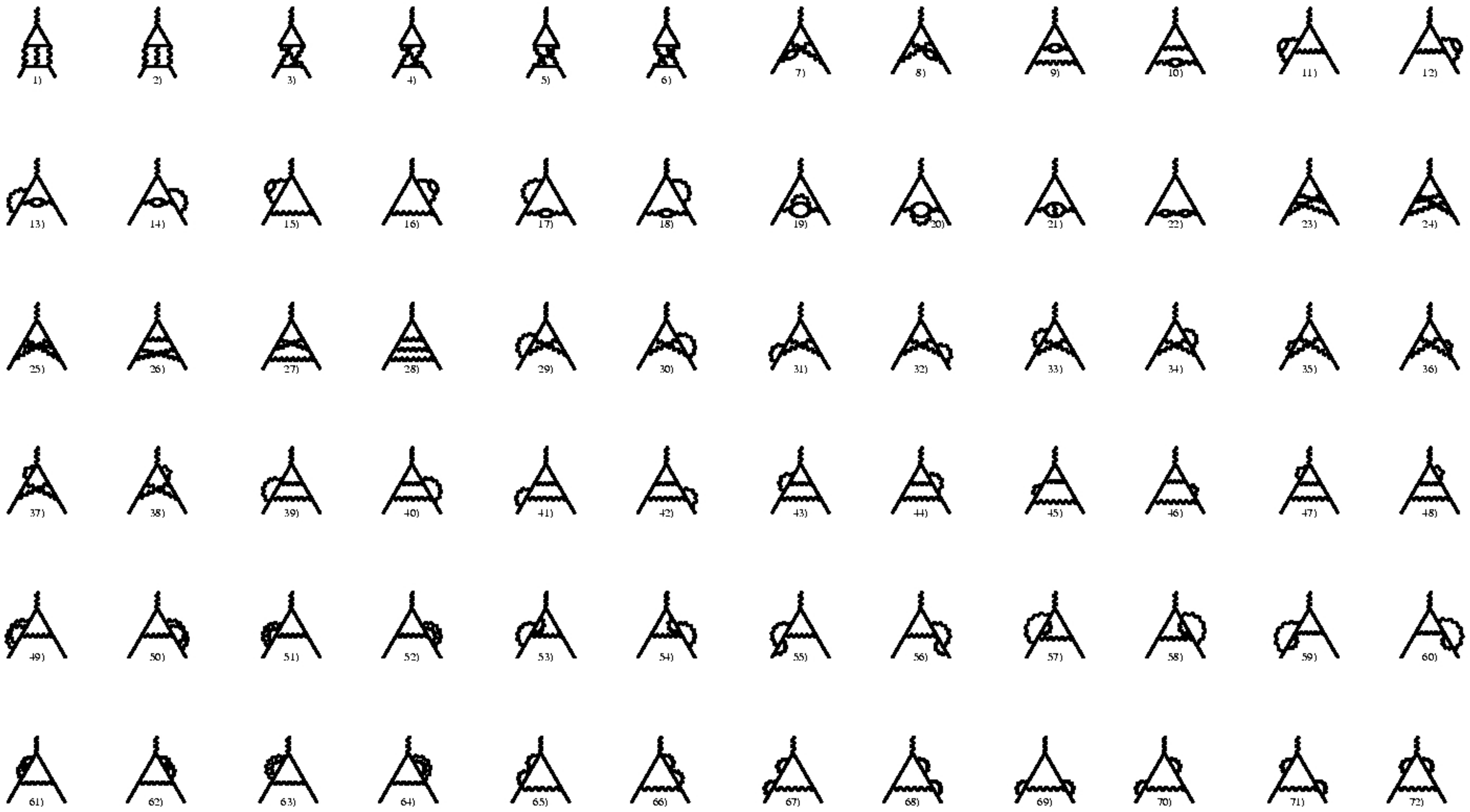




$(g\text{-}2)_\ell$ ℓ=e,μ,τ



$$a_e = a_\mu = a_\tau = \frac{\alpha}{2\pi}$$

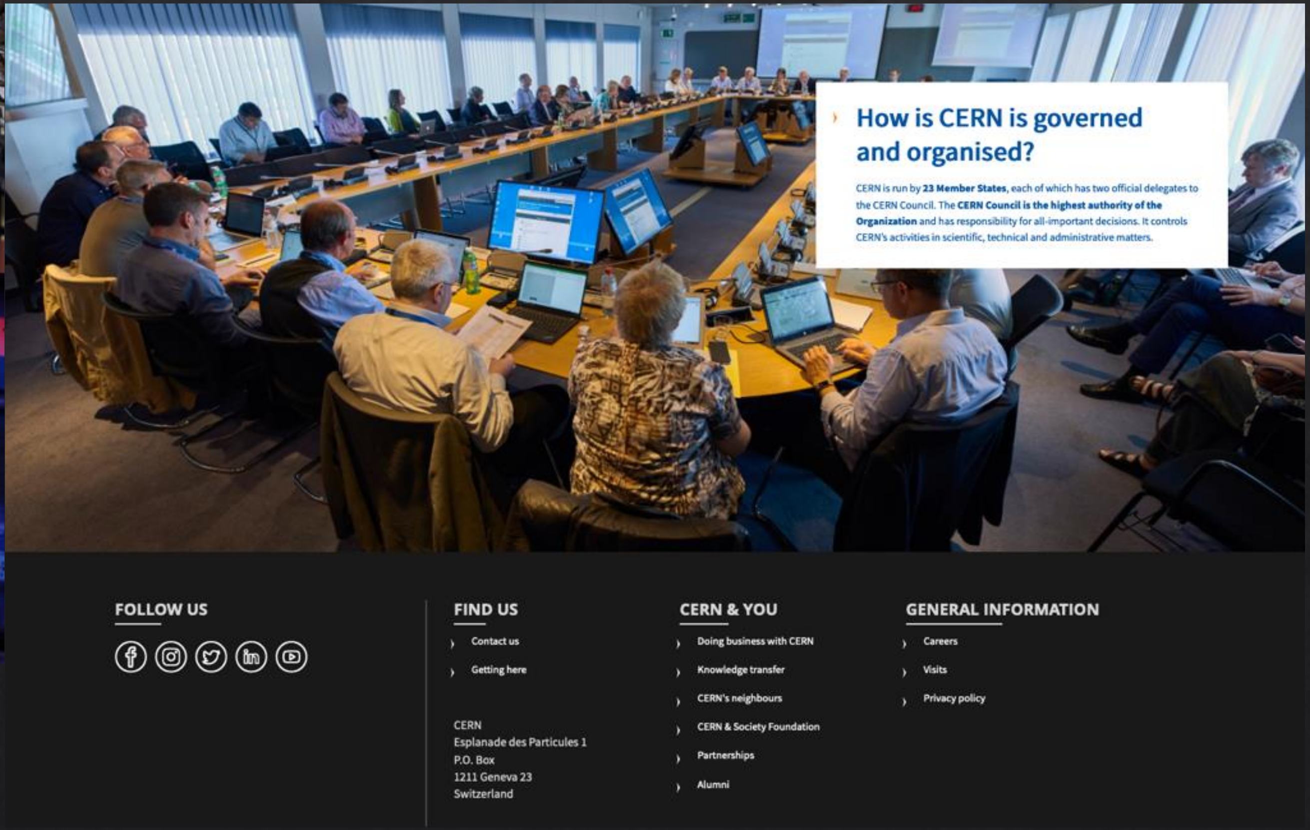


3. Cum producem particule elementare?

- metode simple pentru electroni, protoni (e.g. ionizări)
- radiații cosmice
- reactori nucleari
- acceleratori de particule

Accelerating Science and Innovation

CERN (*Conseil Européen pour la Recherche Nucléaire 1954*) is often referred to as the European Laboratory for Particle Physics.



https://home.cern/

Romania

Romania entered into direct collaboration with CERN in the early 1990s. Even before becoming a CERN member, Romania made significant contributions to the ALICE, ATLAS and LHCb experiments.

Romania became CERN's 22nd Member State on 17 July 2016. The Institute of Atomic Physics is the funding agency covering the Romanian participation in the CERN experiments. In the current national plan, which started in 2016, the Romanian institutions contribute to the following experiments: ALICE, ATLAS, LHCb, WLCG, ISOLDE, NA62, n_TOF, MoEDAL and WA105. The participations are evaluated yearly by an International Scientific Advisory Board. There are four national R&D institutes and six universities from six cities involved in the CERN collaborations, with IFIN-HH being the largest stakeholder. The number of scientists and engineers involved is over 100 and it has been increasing steadily in the last decade.

This page was last updated on 12 May, 2020

CERN contact(s): P. Wells, O. Capatina

116 CERN users - Overview of participation

Industrial Liaison | Knowledge Transfer | Scientific Computing

Teacher Student Forum | Communication | Outreach

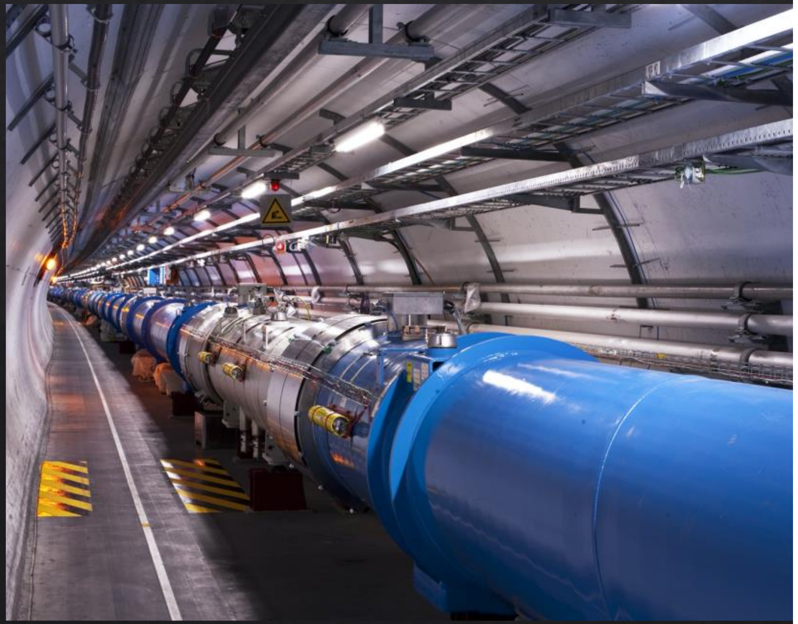
Experiments	WLCG participation
ALICE , ATLAS , LHCb , DIRAC , ISOLDE , NA62 , CLICdp	Tier 2

Member States

Austria
Belgium
Bulgaria
Czech Republic
Denmark
Finland
France
Germany
Greece
Hungary
Israel
Italy
Netherlands
Norway
Poland
Portugal
Romania
Serbia
Slovak Republic
Spain
Sweden
Switzerland
United Kingdom

https://www.ifa-mg.ro/cern/programul-cern-ro.php

MINISTERUL CERCETĂRII, INOVĂRII ȘI DIGITALIZĂRII

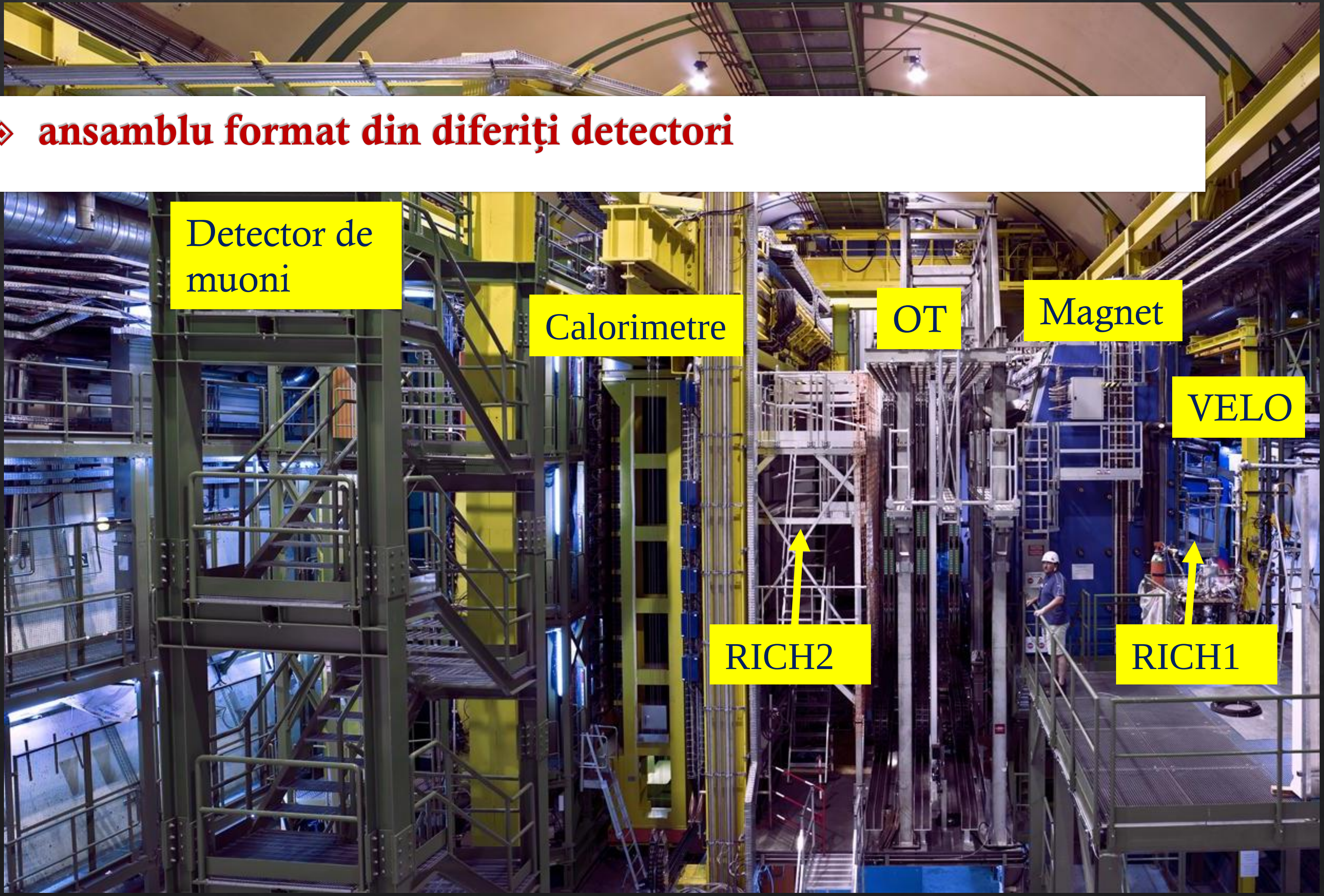


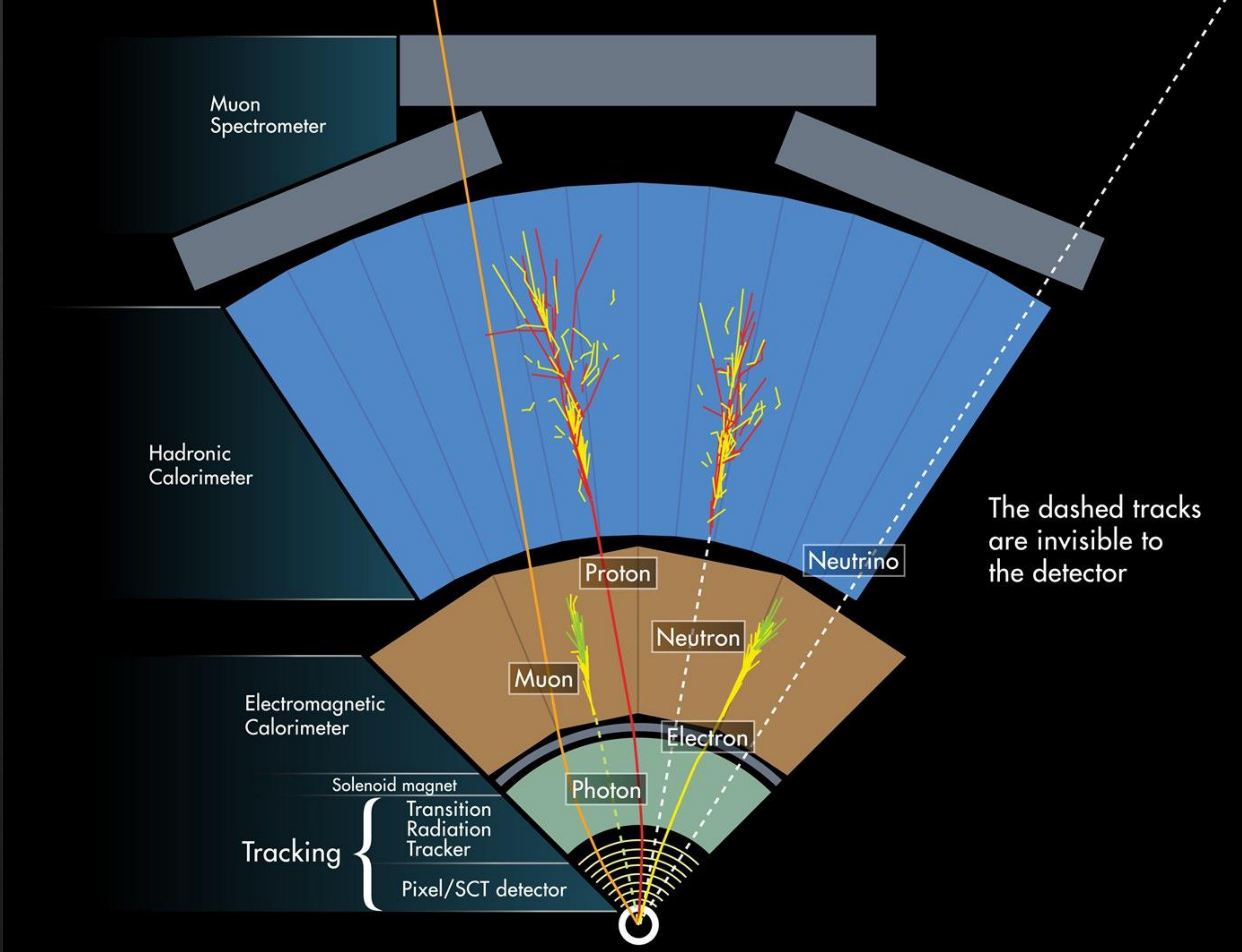
Proiecte in derulare

Experiment	Conducator proiect(CO)/ Parteneri	Director proiect
ALICE	CO: IFIN-HH	Mihai PETROVICI mpetro@ifin.nipne.ro
	CO: ISS	Alexandru Florin DOBRIN alexandru.florin.dobrin@cern.ch
ATLAS EXPERIMENT and RD51	CO: IFIN-HH	Calin ALEXA calin.alexa@cern.ch
	P1: ITIM-CJ	
	P2: UPB	
	P3: UAIC	
	P4: UVT	
	P5: UTB	
	P6: UB	
LHCb	CO: IFIN-HH	Florin MACIUC florin.maciuc@cern.ch
	P1: USV	
WLCG	CO: IFIN-HH	Mihnea DULEA mihnea.dulea@nipne.ro
	P1: ISS	
	P2: ITIM-CJ	
	P3: UAIC	
	P4: UPB	
ISOLDE	CO: IFIN-HH	Constantin MIHAI constantin.mihai@nipne.ro
n_TOF	CO: IFIN-HH	Alexandru NEGREȚ alnegret@tandem.nipne.ro
NA62	CO: IFIN-HH	Alexandru-Mario BRAGADIREANU mario.bragadireanu@nipne.ro
RD50	CO: INCDFM	Ioana PINTILIE ioana@infim.ro
MoEDAL	CO: ISS	Vlad POPA vpopa@spacescience.ro
WA105	CO:UB-FF	Ionel LAZANU ionel.lazanu@g.unibuc.ro
DsTau NA65	CO:ISS	Elena FIRU elena.firu@spacescience.ro

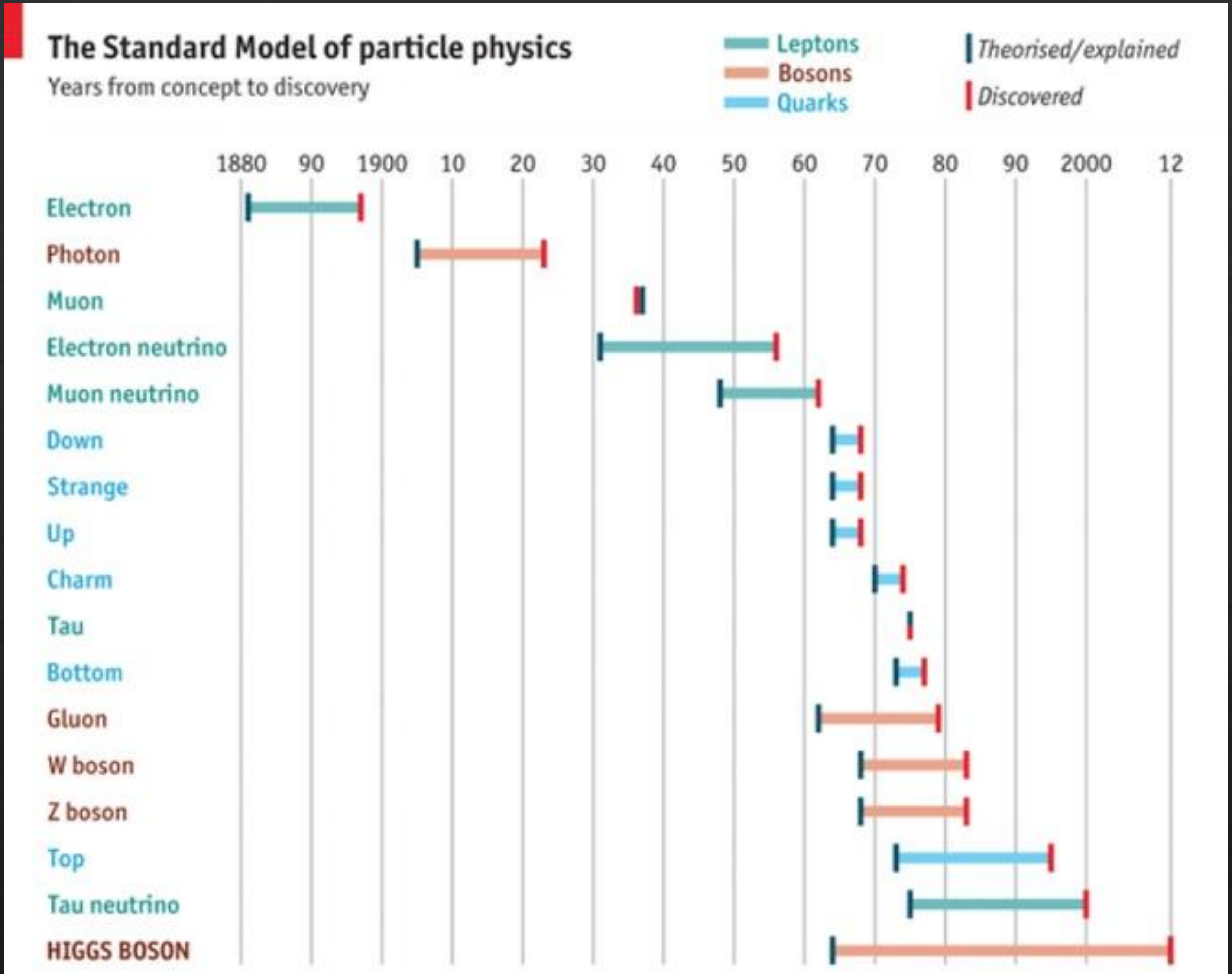
4. Cum detectăm particule elementare?

- **ansamblu format din diferiți detectori**





The dashed tracks are invisible to the detector


The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880
90
1900
10
20
30
40
50
60
70
80
90
2000
12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS BOSON

Fizica particulelor

1. Care sunt particulele elementare (ce proprietăți au – masă, sarcină electrică, spin, …)?
2. Cum interacționează? - De unde obținem informații?
3. Cum producem particule elementare?
4. Cum detectăm particule elementare?

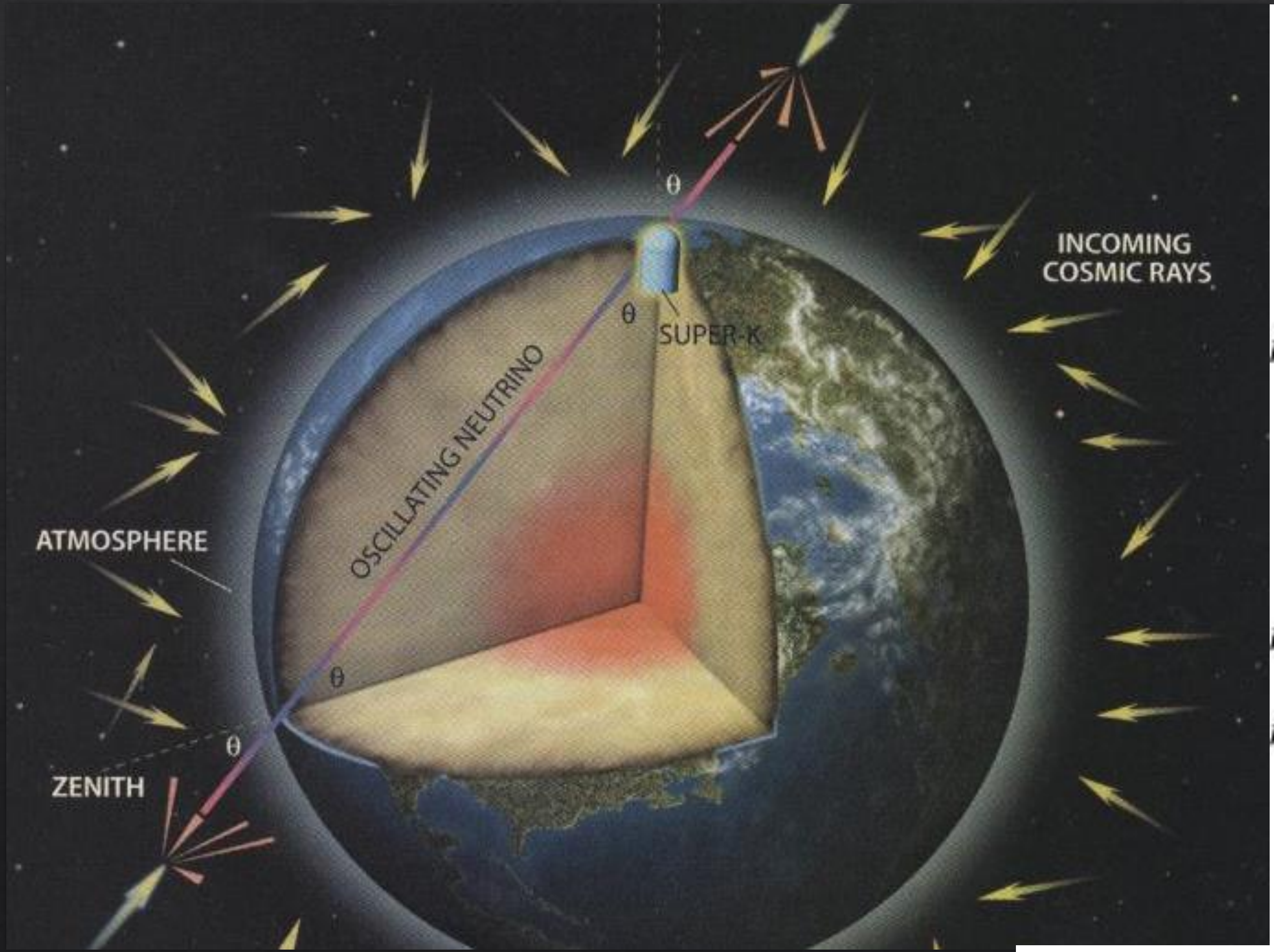
- **Particle Physics**
- **Particle Detectors**

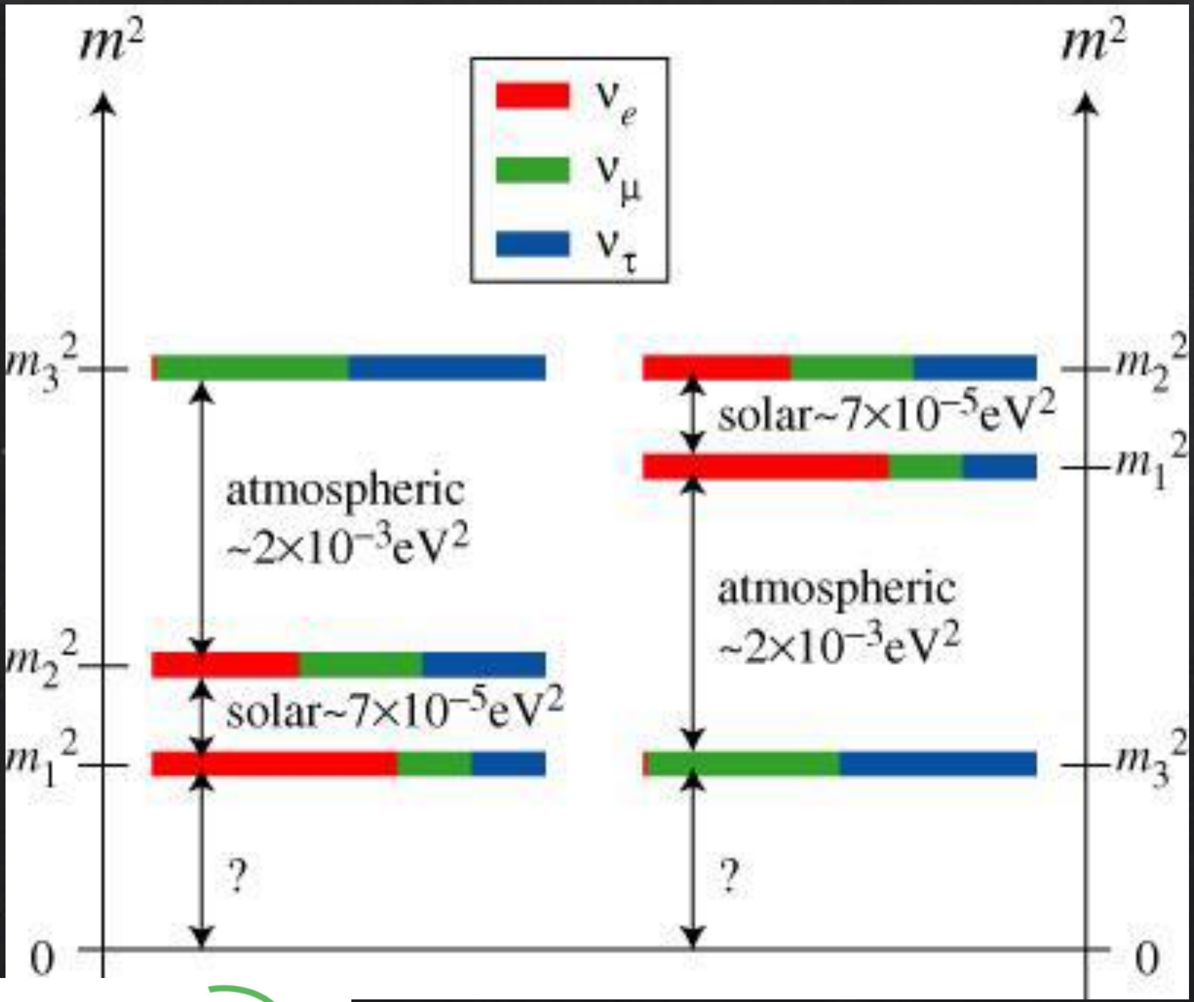
- Din ce este constituită materia?
- Din ce este compus universul?
- Care este originea universului și cum a evoluat?
- De ce se comportă așa universul?
- Cum va evolua?
- ….

Modelul Standard –
răspunsul la toate întrebările?

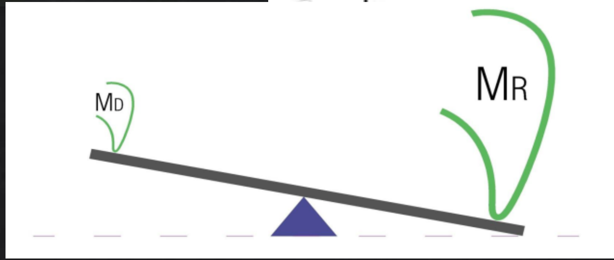
- **NU!**

Cum acomodăm în teorie masa neutrinilor?

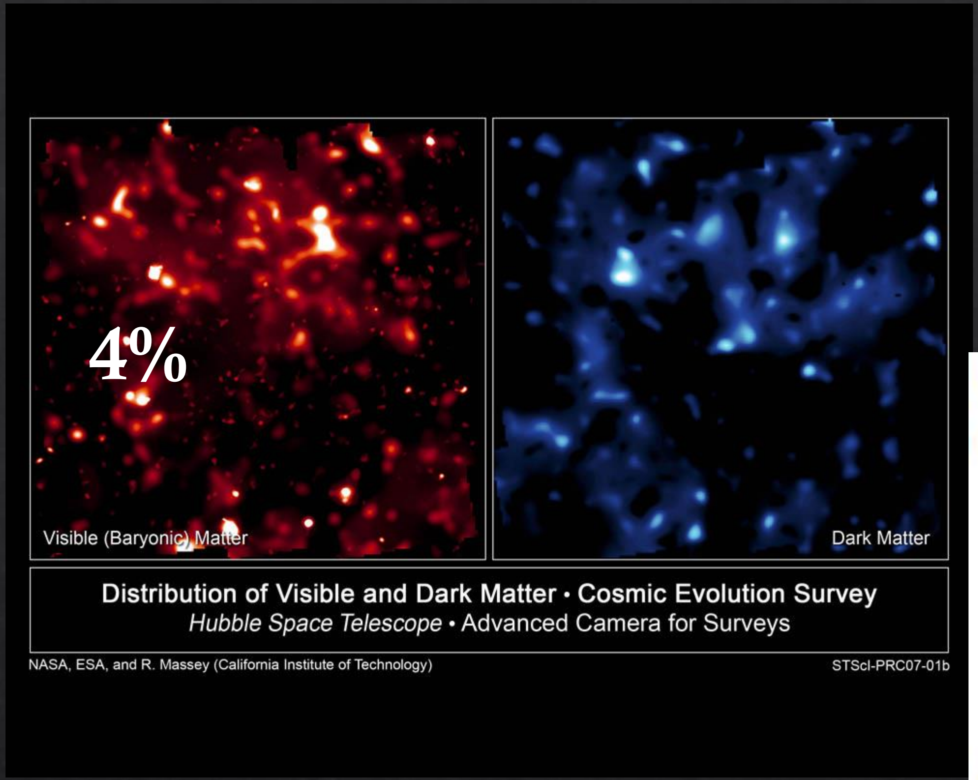


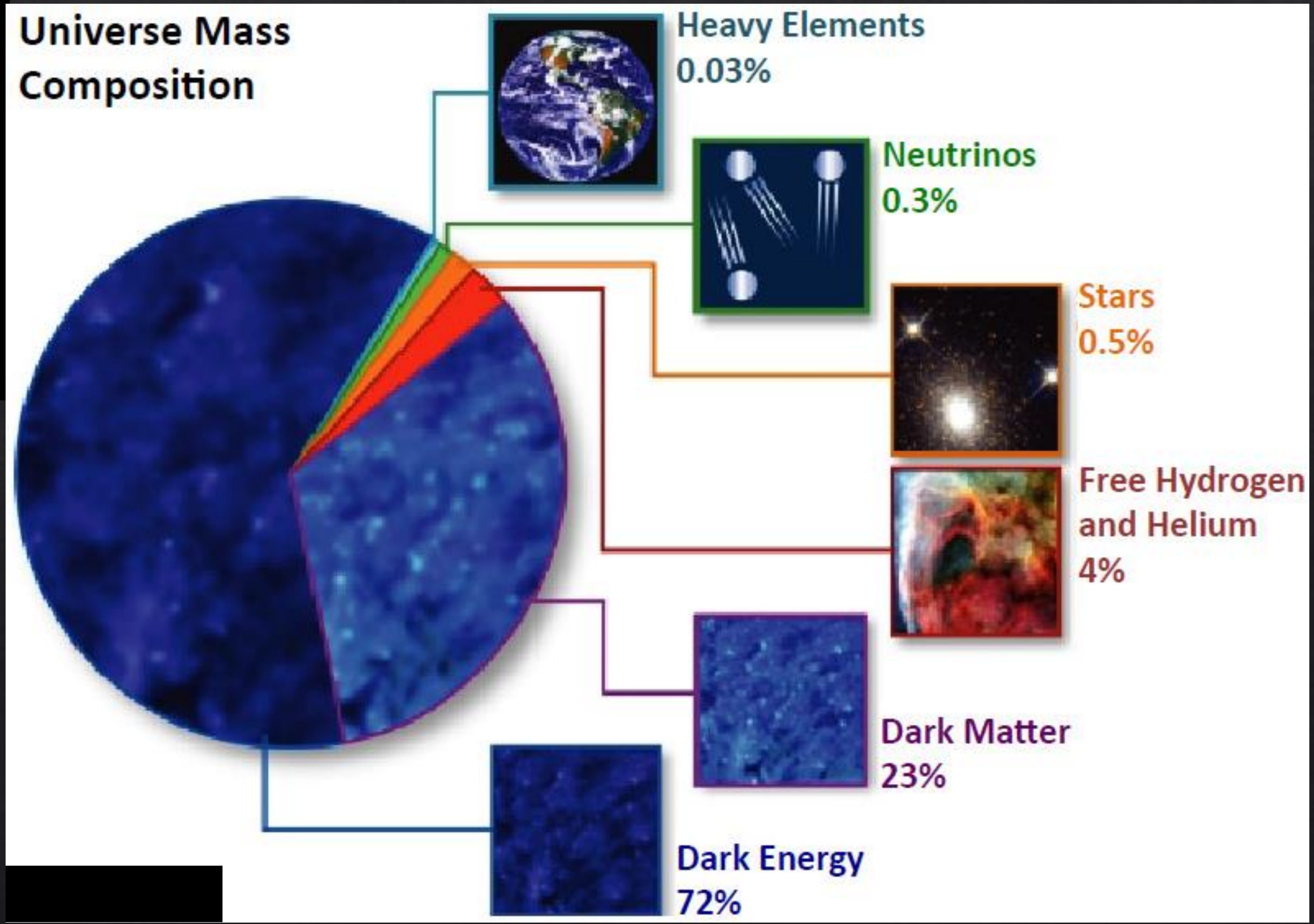


matricea de mixing a neutrinilor?



Ce este ,,dark matter"?

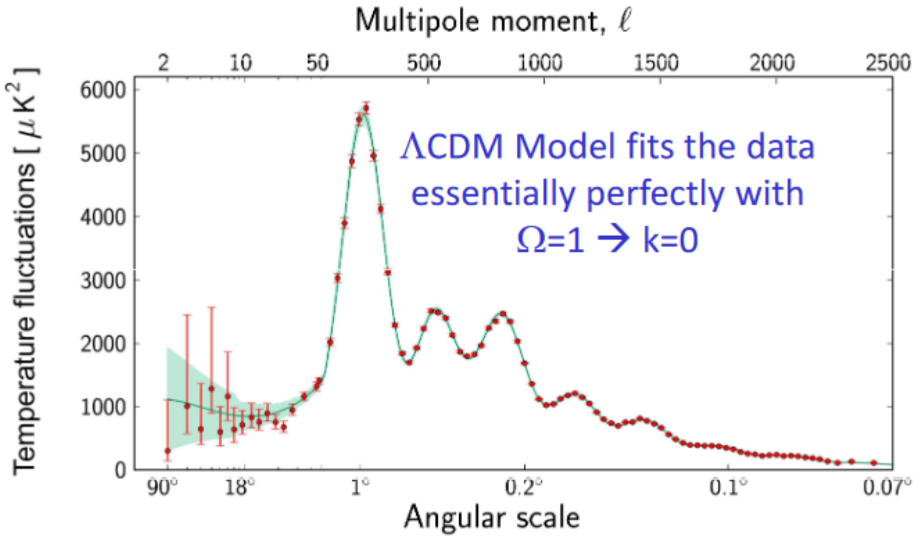


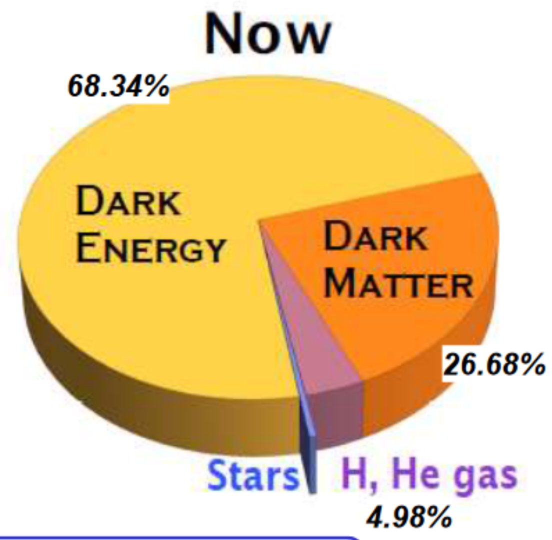


Urmează: **Pascal Pralavorio's on Dark matter**

Cosmic microwave background

- **Use this photon flux to know the composition of the Universe**
  - Decompose data in spherical harmonics
  - Amplitude and position of "acoustic" peaks gives the composition of the Universe





Cosmology is making precision measurements … **and**
we don't know 95% of the Universe and 85% of the matter !

De ce în univers există mai multă materie decât antimaterie?

- Există cantități mari de materie, dar nu și dovada unor cantități mari de antimaterie.

violarea conservării sarcinii și parității
CP – charge-parity

beauty

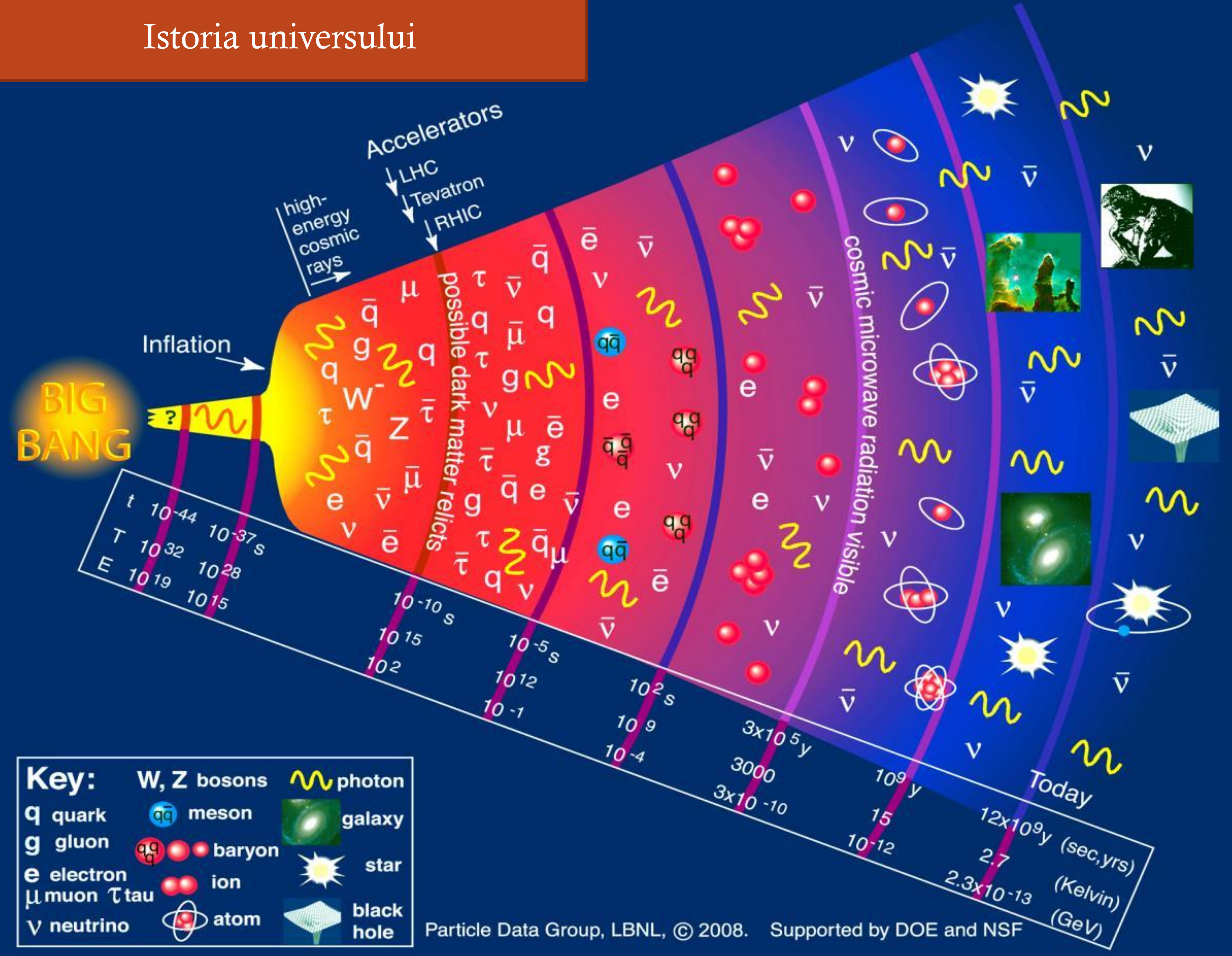
B^0

CP

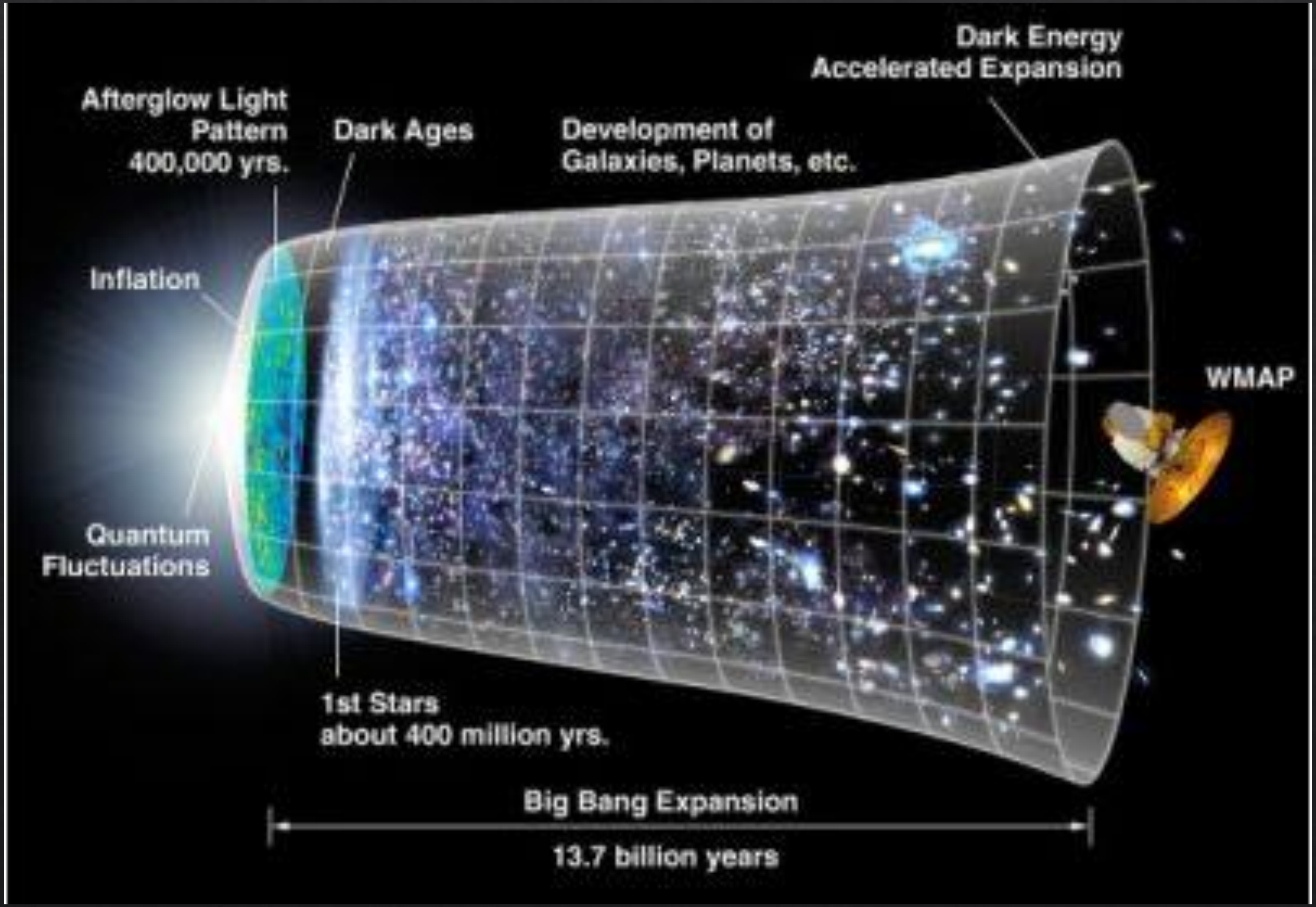
anti-beauty

$\overline{B^0}$

Istoria universului



Ce face universul astăzi și cum va evolua?



NASA/WMAP Science Team

Modelul Standard – răspunsul la toate întrebările?

- **NU!**

- **Extensions of the Standard Model of elementary particles**

Particle Listings

R.L. Workman *et al.* (Particle Data Group), Prog. Theor. Exp. Phys. **2022**, 083C01 (2022) and 2023 update

Cut-off date for Listings/Summary Tables was Jan. 15, 2023. Files can be downloaded directly by clicking on the icon: PDF. For a key to the listings click here.

Expand/Collapse All

Gauge & Higgs Bosons

- gamma
- g (gluon)
- graviton
- W boson
- Z boson
- H
- Neutral Higgs Bosons, Searches for
- Charged Higgs Bosons ($H^{\pm}$ and $H^{\pm\pm}$), Searches for
- Heavy Bosons, Other Than Higgs Bosons, Searches for
- Axions (A^0) and Other Very Light Bosons, Searches for

Leptons (e, mu, tau, neutrinos, heavy leptons ...)

electron	PDF	pdgLive
muon	PDF	pdgLive
tau	PDF	pdgLive
Heavy Charged Lepton Searches	PDF	pdgLive
Neutrino Properties	PDF	pdgLive
Number of Neutrino Types	PDF	pdgLive
Double-beta Decay	PDF	pdgLive
Neutrino Mixing	PDF	pdgLive
Heavy Neutral Leptons, Searches for	PDF	pdgLive

Quarks (u,d,s,c,b,t...)

LIGHT QUARKS --- u, d, s	PDF	pdgLive
c quark	PDF	pdgLive
b quark	PDF	pdgLive
t quark	PDF	pdgLive
b' quark (4**th Generation)	PDF	pdgLive
t' quark (4**th Generation)	PDF	pdgLive
Free Quark Searches	PDF	pdgLive

https://pdglive.lbl.gov

Fizica particulelor

1. **Care sunt particulele elementare (ce proprietăți au – masă, sarcină electrică, spin, …)?**
2. **Cum interacționează? - De unde obținem informații?**
3. **Cum producem particule elementare?**
4. **Cum detectăm particule elementare?**

- **Particle Physics**
- **Particle Detectors**