**Roxana Zus**

Facultatea de Fizică

Universitatea din București

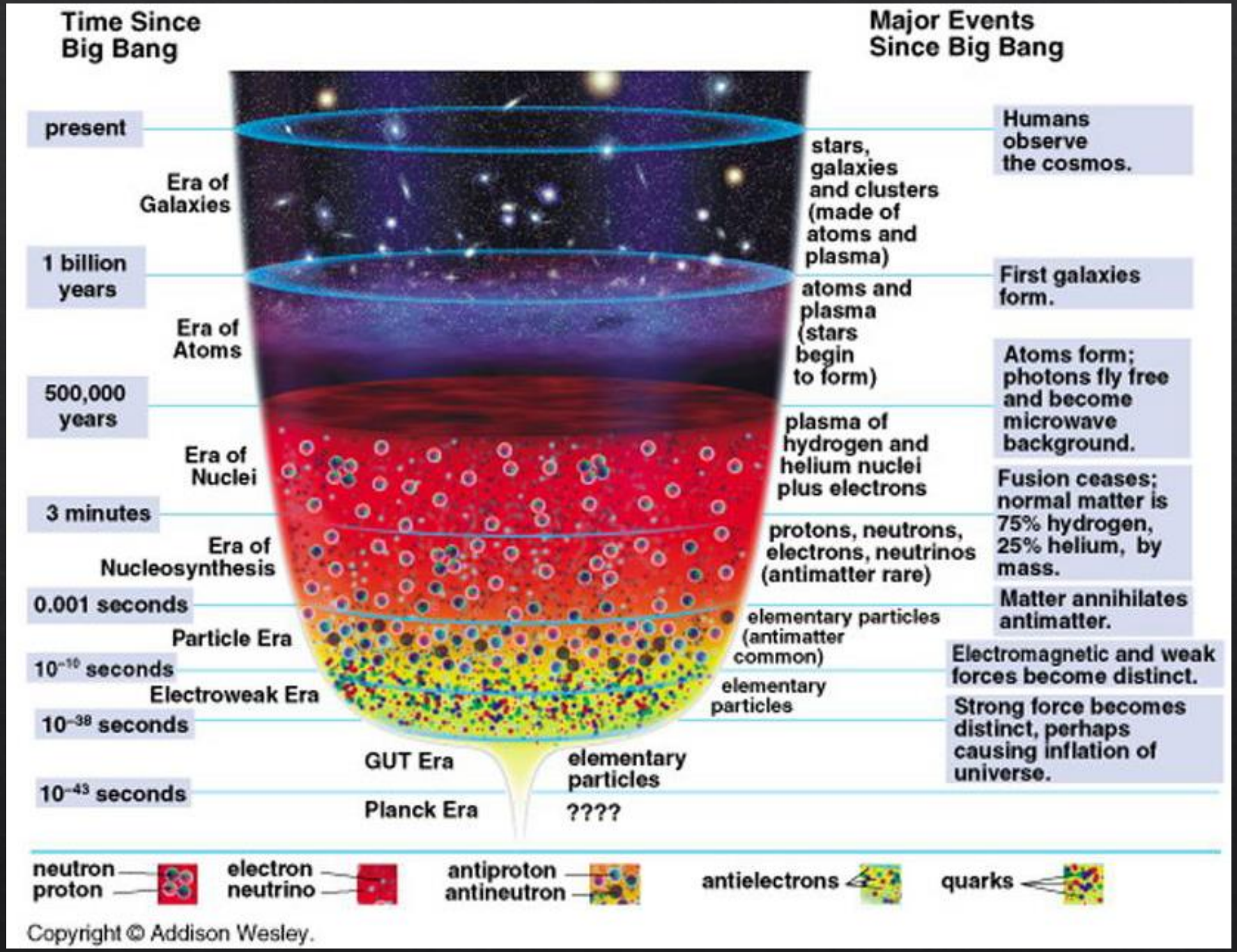
# Introducere în fizica particulelor la energii înalte II

"What is the Universe made of?"
High Energy Physics summer school

3 septembrie 2024

# Întrebări

- 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?
- ....

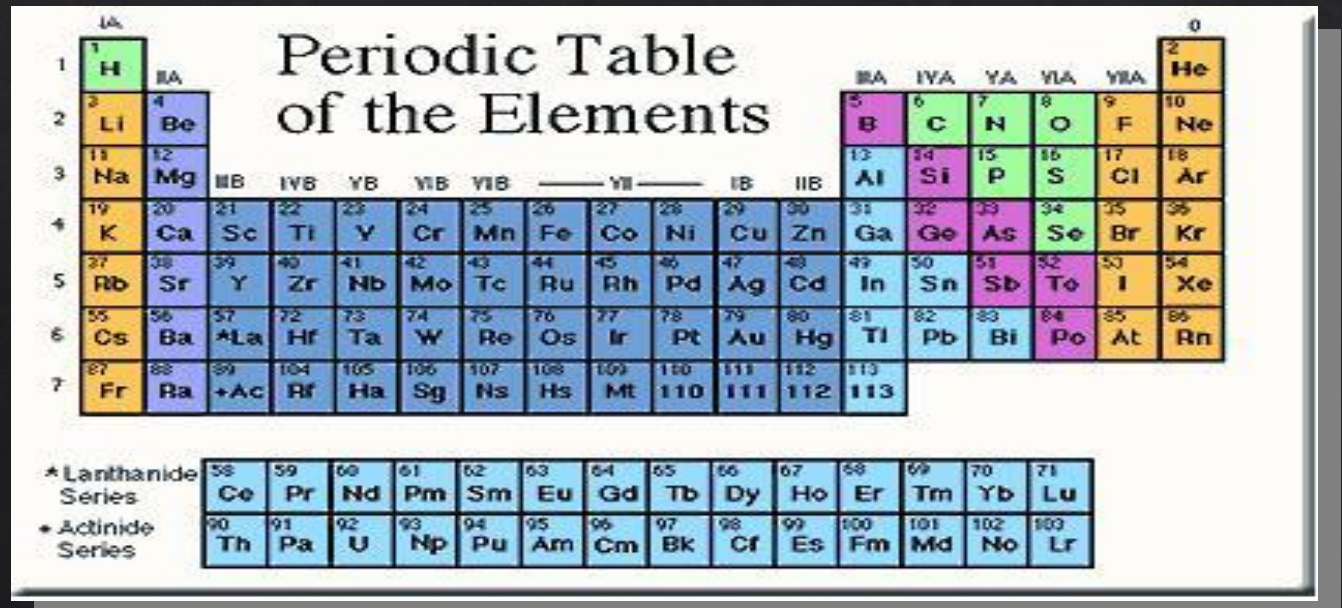


# Care sunt elementele din care este constituita materia?


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.

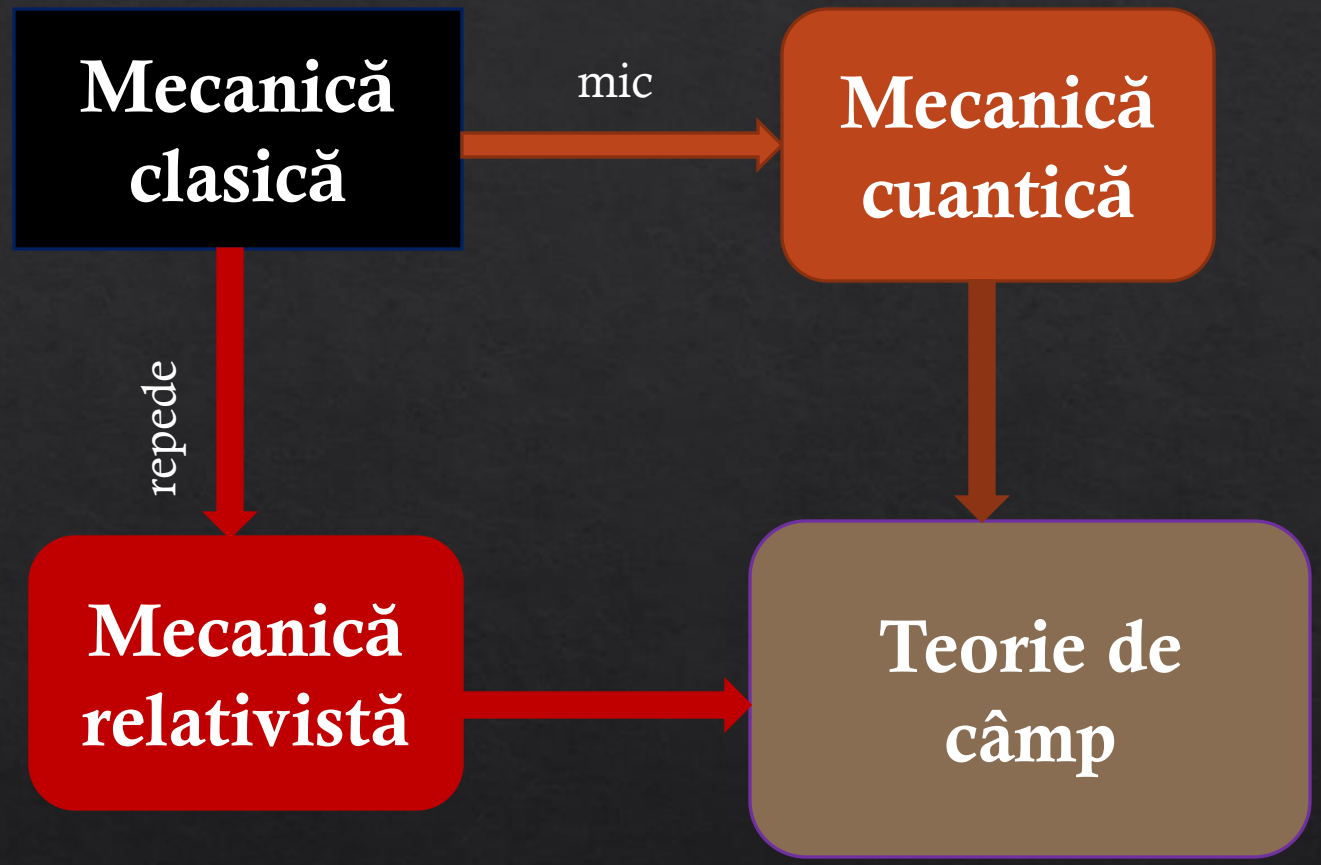
- începutul secolului XX:
  - **domeniul relativist** (mecanica Newtoniană nu poate fi folosită la viteze foarte mari)
  - **domeniul microscopic** (fizica clasică nu poate fi folosită la nivel microscopic – e.g. pentru descrierea atomilor și moleculelor, a interacției cu câmpul electromagnetic etc.)

Ce legi folosim?

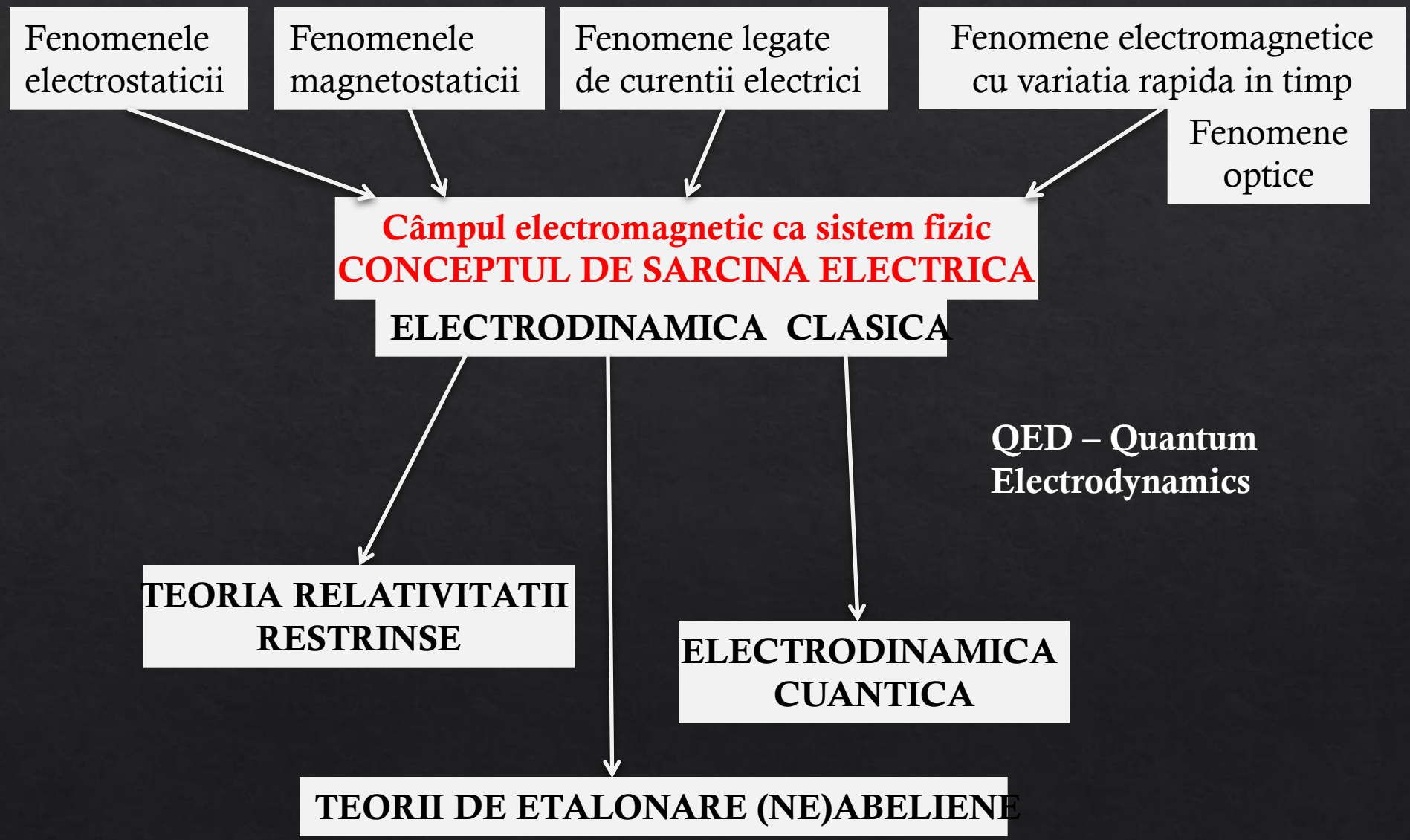
Ce mecanică folosim?

Legea atracției universale

Legile de mișcare ale lui Newton – mecanica clasică

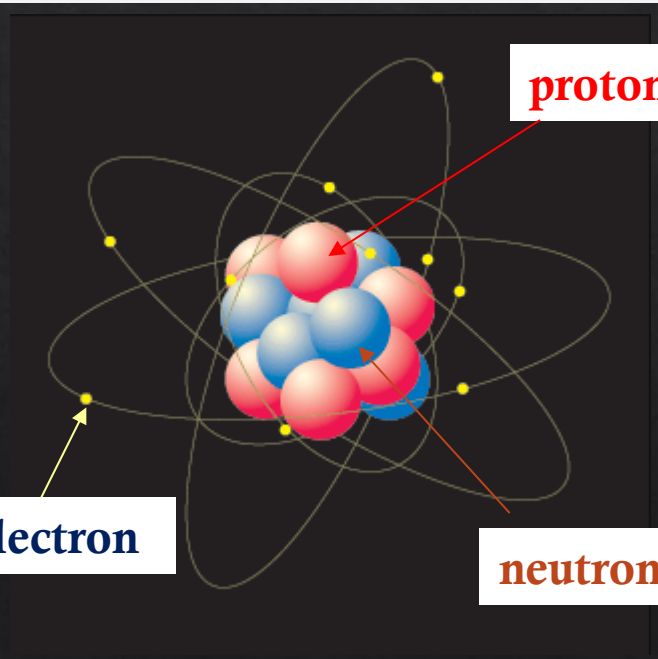

Mecanică clasică
mic
Mecanică cuantică
repede
Mecanică relativistă
Teorie de câmp

# Câmpul electromagnetic ca sistem fizic



# Atomii

Atomii:
- protoni și neutroni în nucleu
- electroni



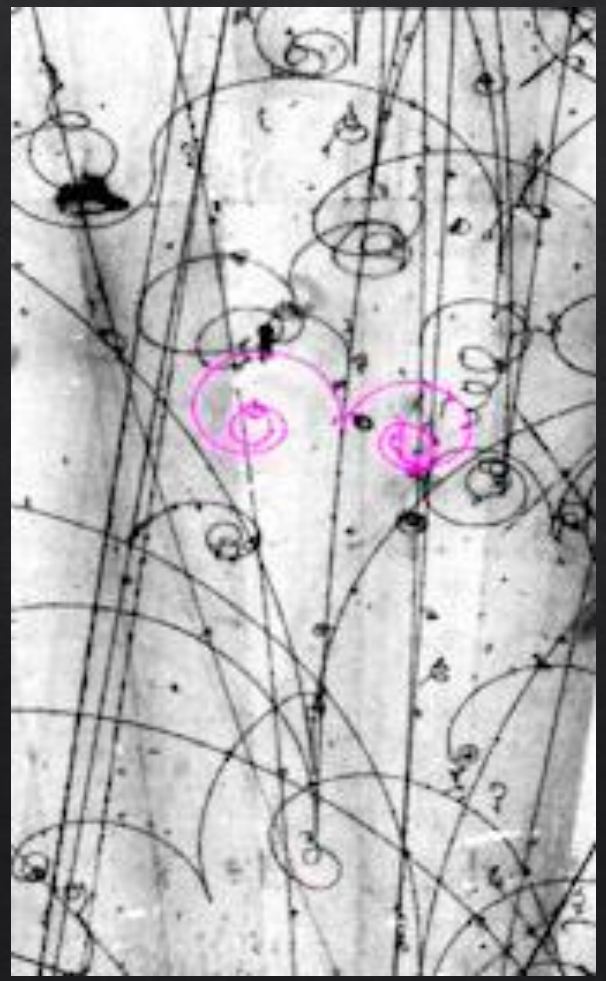

**Sunt protonii și neutronii particule elementare?**

# 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?

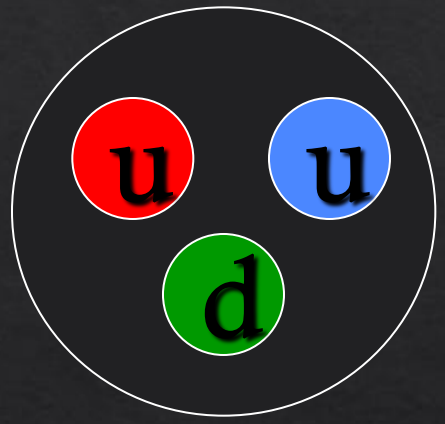
**INTERACȚIA TARE**

- 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*

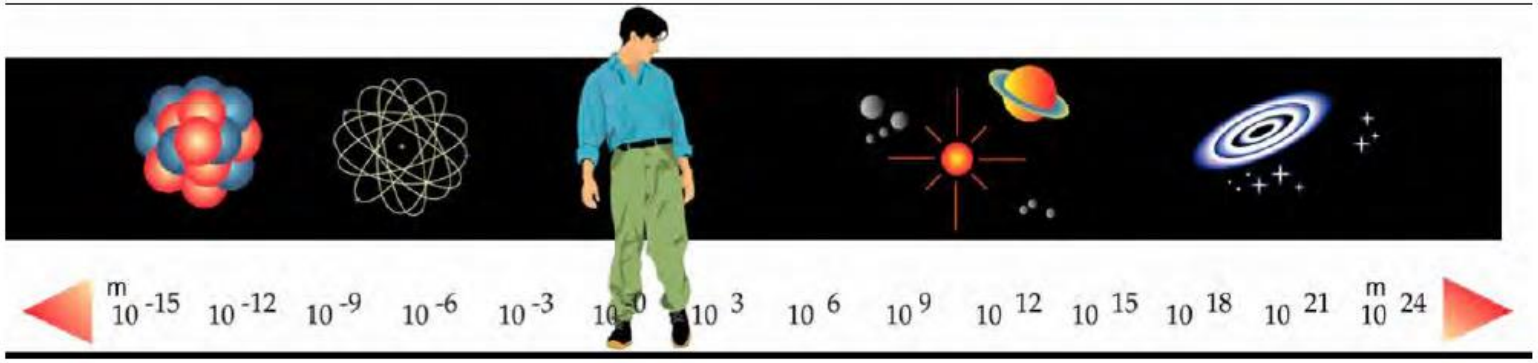
u - cuarcul up – sarcină electrică + 2/3

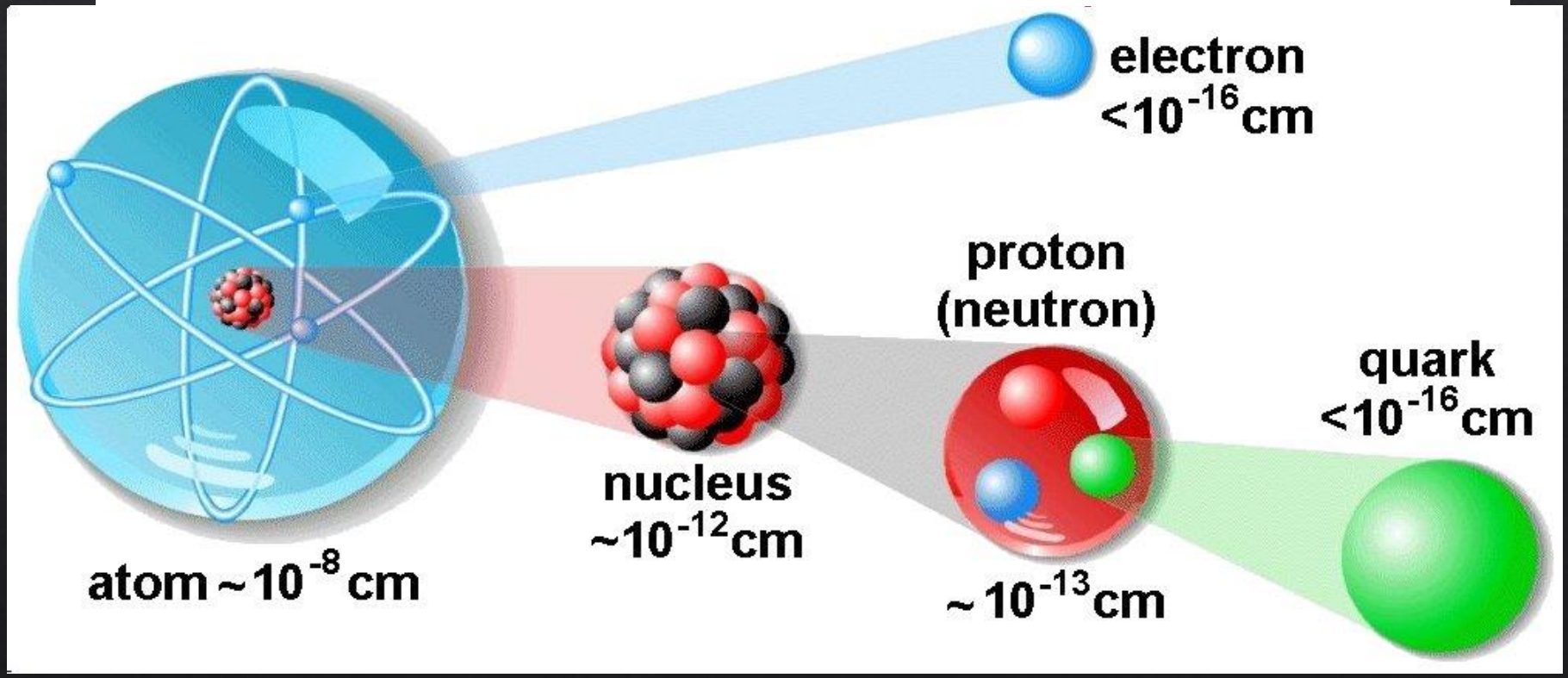
d - cuarcul down – sarcină electrică –1/3

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

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

# Structura materiei (astăzi!)

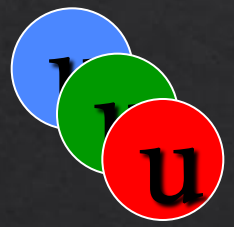


# Cuarcii și culorile

**QCD – Quantum chromodynamics**

Fiecare cuarc poate avea 3 “culori”




**up**

+2/3


**down**

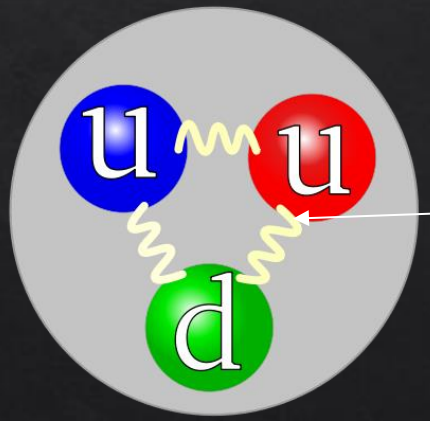
-1/3

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 |
| $\boldsymbol{K_0^*(800)^0}$ | **9000311**$^*$ |
| $\boldsymbol{K_0^*(800)^+}$ | **9000321**$^*$ |
| $K_0^*(1430)^0$ | 10311 |
| $K_0^*(1430)^+$ | 10321 |
| $K(1460)^0$ | 100311 |
| $K(1460)^+$ | 100321 |
| $\boldsymbol{K(1830)^0}$ | **9010311**$^*$ |
| $\boldsymbol{K(1830)^+}$ | **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 |
| $\boldsymbol{K_1(1650)^0}$ | **9000313**$^*$ |
| $\boldsymbol{K_1(1650)^+}$ | **9000323**$^*$ |
| $K^*(1680)^0$ | 30313 |

| CHARMED MESONS | |
|---|---|
| $D^+$ | 411 |
| $D^0$ | 421 |
| $\boldsymbol{D_0^*(2400)^+}$ | 10411 |
| $\boldsymbol{D_0^*(2400)^0}$ | 10421 |
| $D^*(2010)^+$ | 413 |
| $D^*(2007)^0$ | 423 |
| $D_1(2420)^+$ | 10413 |
| $D_1(2420)^0$ | 10423 |
| $D_1(H)^+$ | 20413 |
| $\boldsymbol{D_1(2430)^0}$ | 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 |
| $\boldsymbol{\chi_{c2}(2P)}$ | **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 |
| $\Delta^{++}$ | 2224 |
| $\Delta^+$ | 2214 |
| $\Delta^0$ | 2114 |
| $\Delta^-$ | 1114 |

| STRANGE BARYONS | |
|---|---|
| $\Lambda$ | 3122 |
| $\Sigma^+$ | 3222 |
| $\Sigma^0$ | 3212 |
| $\Sigma^-$ | 3112 |
| $\Sigma^{*+}$ | $3224^d$ |
| $\Sigma^{*0}$ | $3214^d$ |
| $\Sigma^{*-}$ | $3114^d$ |
| $\Xi^0$ | 3322 |
| $\Xi^-$ | 3312 |
| $\Xi^{*0}$ | $3324^d$ |
| $\Xi^{*-}$ | $3314^d$ |
| $\Omega^-$ | 3334 |

| CHARMED BARYONS | |
|---|---|
| $\Lambda_c^+$ | 4122 |
| $\Sigma_c^{++}$ | 4222 |
| $\Sigma_c^+$ | 4212 |
| $\Sigma_c^0$ | 4112 |
| $\Sigma_c^{*++}$ | 4224 |
| $\Sigma_c^{*+}$ | 4214 |

| BOTTOM BARYONS | |
|---|---|
| $\Lambda_b^0$ | 5122 |
| $\Sigma_b^-$ | 5112 |
| $\Sigma_b^0$ | 5212 |
| $\Sigma_b^+$ | 5222 |
| $\Sigma_b^{*-}$ | 5114 |
| $\Sigma_b^{*0}$ | 5214 |
| $\Sigma_b^{*+}$ | 5224 |
| $\Xi_b^-$ | 5132 |
| $\Xi_b^0$ | 5232 |
| $\Xi_b^{\prime-}$ | 5312 |
| $\Xi_b^{\prime0}$ | 5322 |
| $\Xi_b^{*-}$ | 5314 |
| $\Xi_b^{*0}$ | 5324 |
| $\Omega_b^-$ | 5332 |
| $\Omega_b^{*-}$ | 5334 |
| $\Xi_{bc}^0$ | 5142 |
| $\Xi_{bc}^+$ | 5242 |
| $\Xi_{bc}^{\prime0}$ | 5412 |
| $\Xi_{bc}^{\prime+}$ | 5422 |
| $\Xi_{bc}^{*0}$ | 5414 |
| $\Xi_{bc}^{*+}$ | 5424 |
| $\Omega_{bc}^0$ | 5342 |
| $\Omega_{bc}^{\prime0}$ | 5432 |

# Universul este alcătuit numai din cuarci și electroni?

*Există și neutrini!*

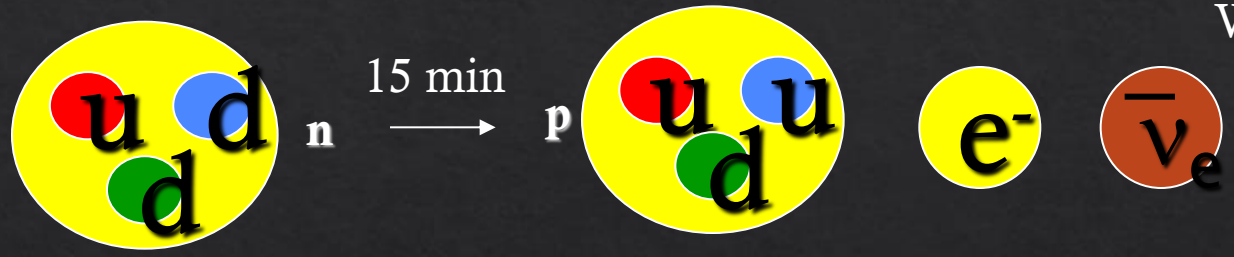

Electronul, protonul și neutronul sunt rari!
Pentru fiecare dintre ei, există1 billion neutrini.

*Neutrinii sunt cele mai abundente particule ale materiei în univers.*


Neutrinii sunt peste tot.

# Dezintegrarea β

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

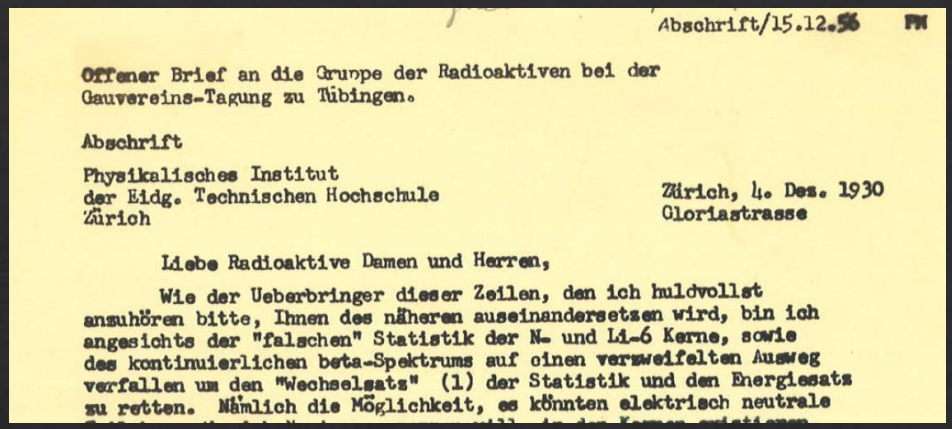



Un neutron se dezintegrează în 15 minute.

**interacție „slabă”!**

**QFD – Quantum flavordynamics**

!



Abschrift/15.12.30 PM

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

Abschrift

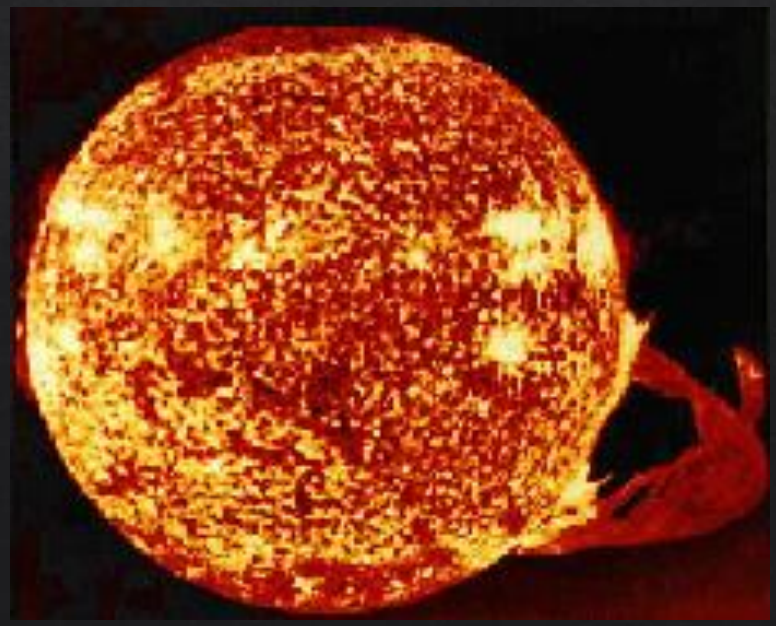
Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Des. 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

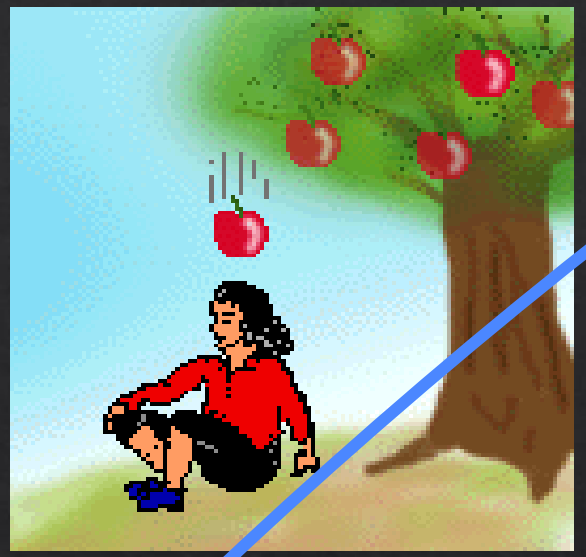
W.Pauli - 1930



# Tipuri de interacție

**Gravitațională**

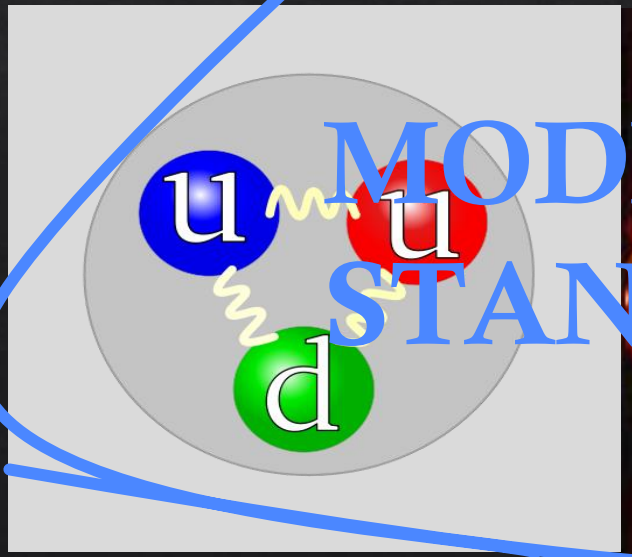
masa



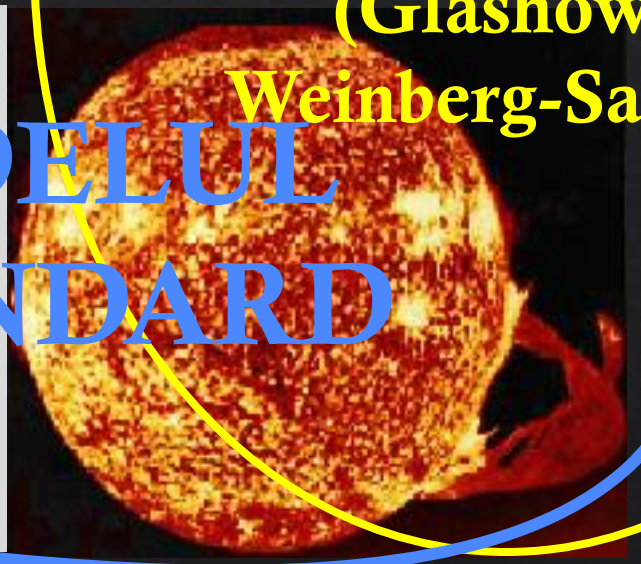

**Electromagnetică**

**ELECTROSLABĂ**
**(Glashow-Weinberg-Salam)**

**Tare**




**MODELUL STANDARD**



**Slabă**

# Cine mediază interacțiile?

**bozonii**

**Gravitațională**

**? graviton ?**


**QED – Quantum Electrodynamics**

**Electromagnetică**

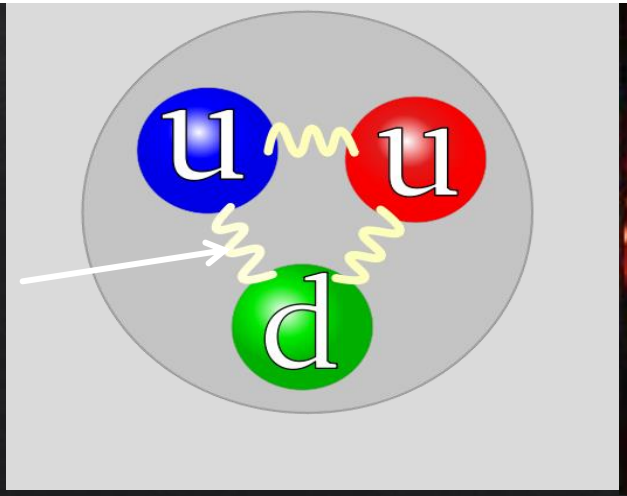
**γ- fotonul**

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

**Tare**

**gluonii**

**QCD – Quantum chromodynamics**



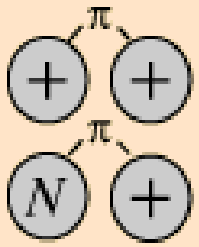
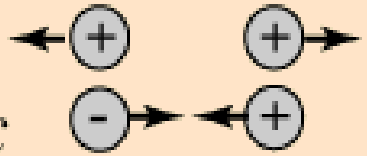
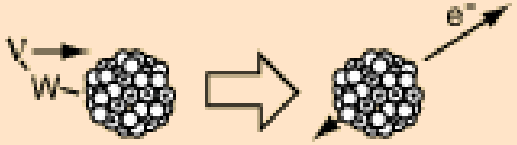
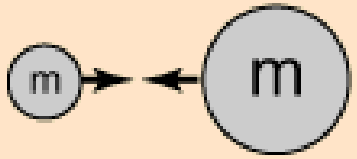

**QFD – Quantum flavordynamics**

**Slabă**

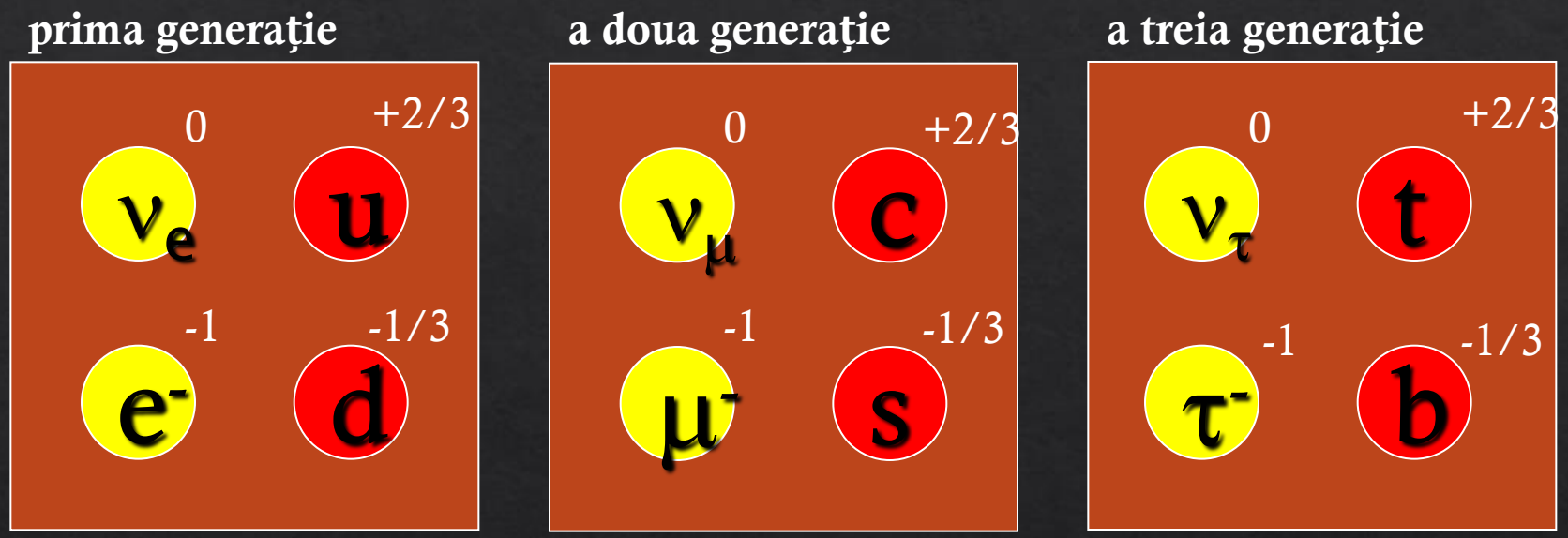
**$W^+$, $W^-$, Z**

# Fundamental Forces

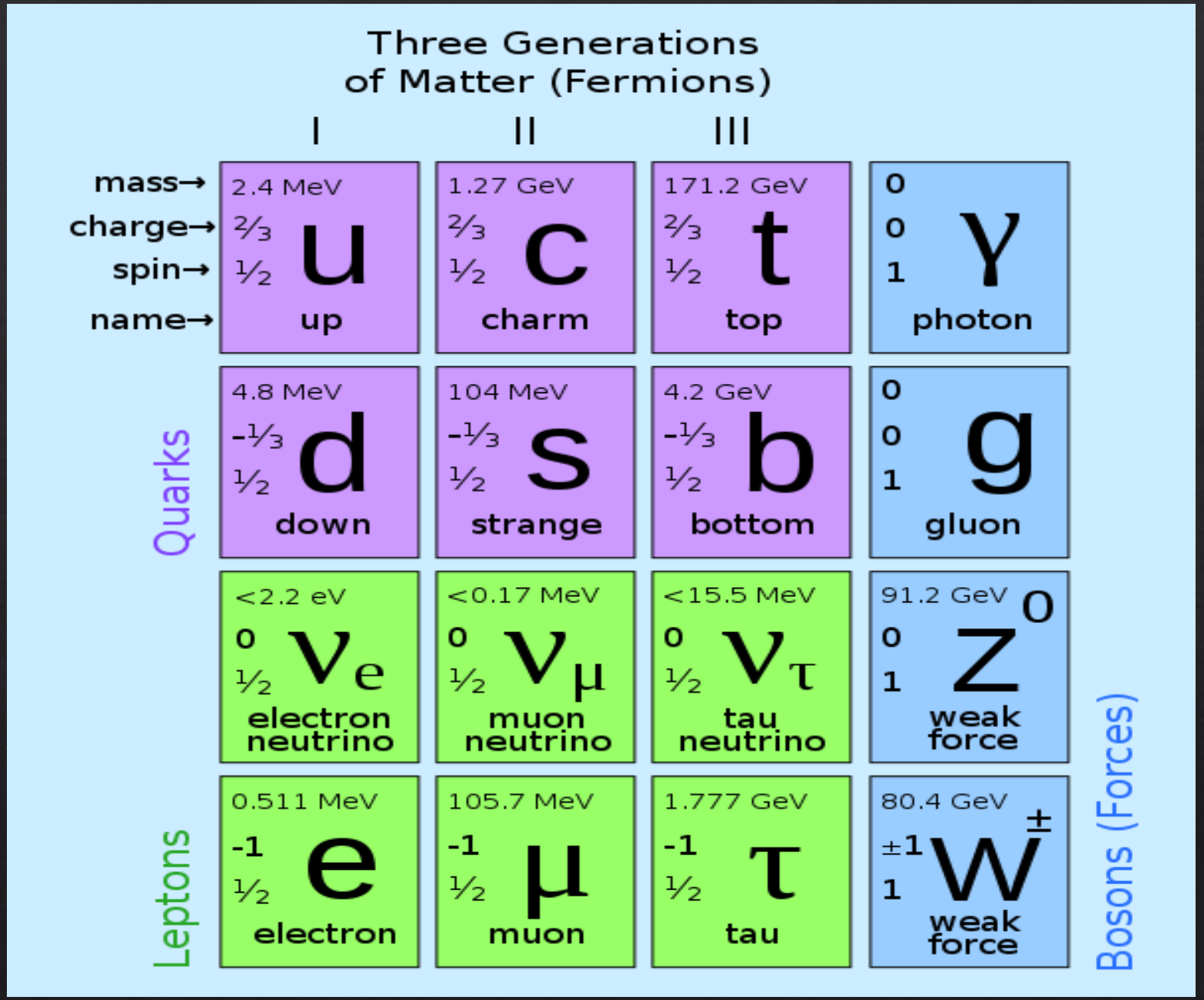
http://hyperphysics.phy-astr.gsu.edu/hbase/Forces/funfor.html

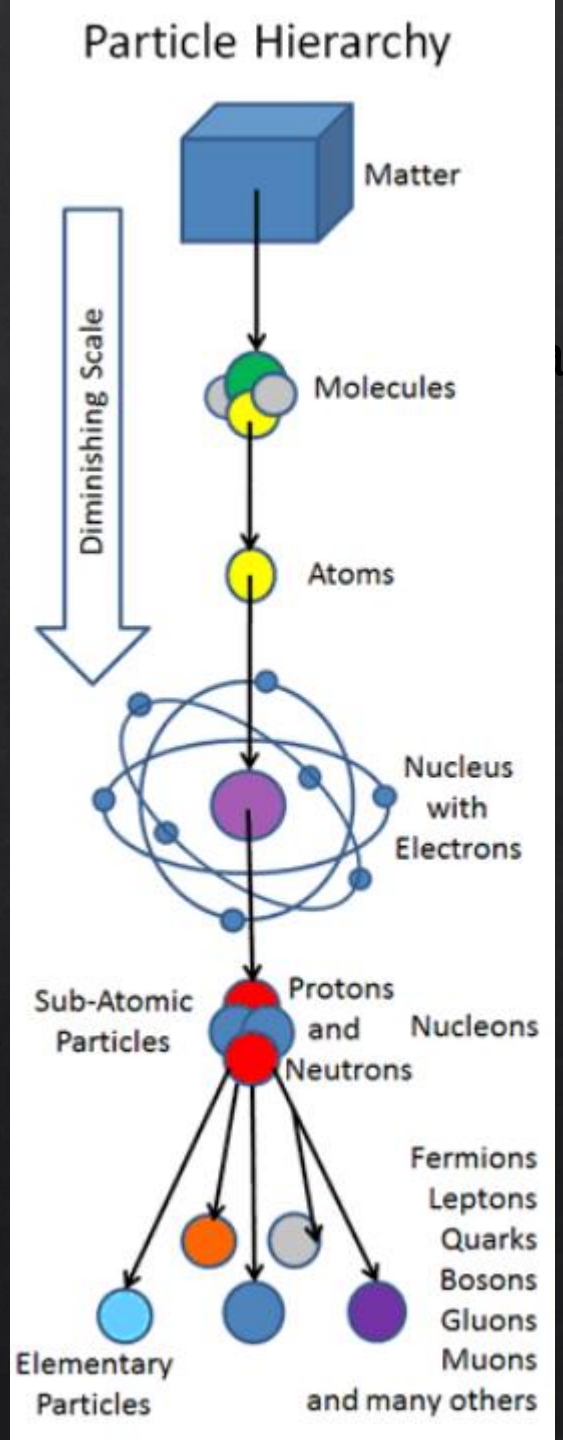
| | | Strength | Range (m) | Particle |
|---|---|---|---|---|
| *Strong* |   Force which holds nucleus togeher | 1 | $10^{-15}$ (diameter of a medium sized nucleus) | gluons, π(nucleons) |
| *Electro-magnetic* |  | $\frac{1}{137}$ | Infinite | photon<br>mass = 0<br>spin = 1 |
| *Weak* |   neutrino interaction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

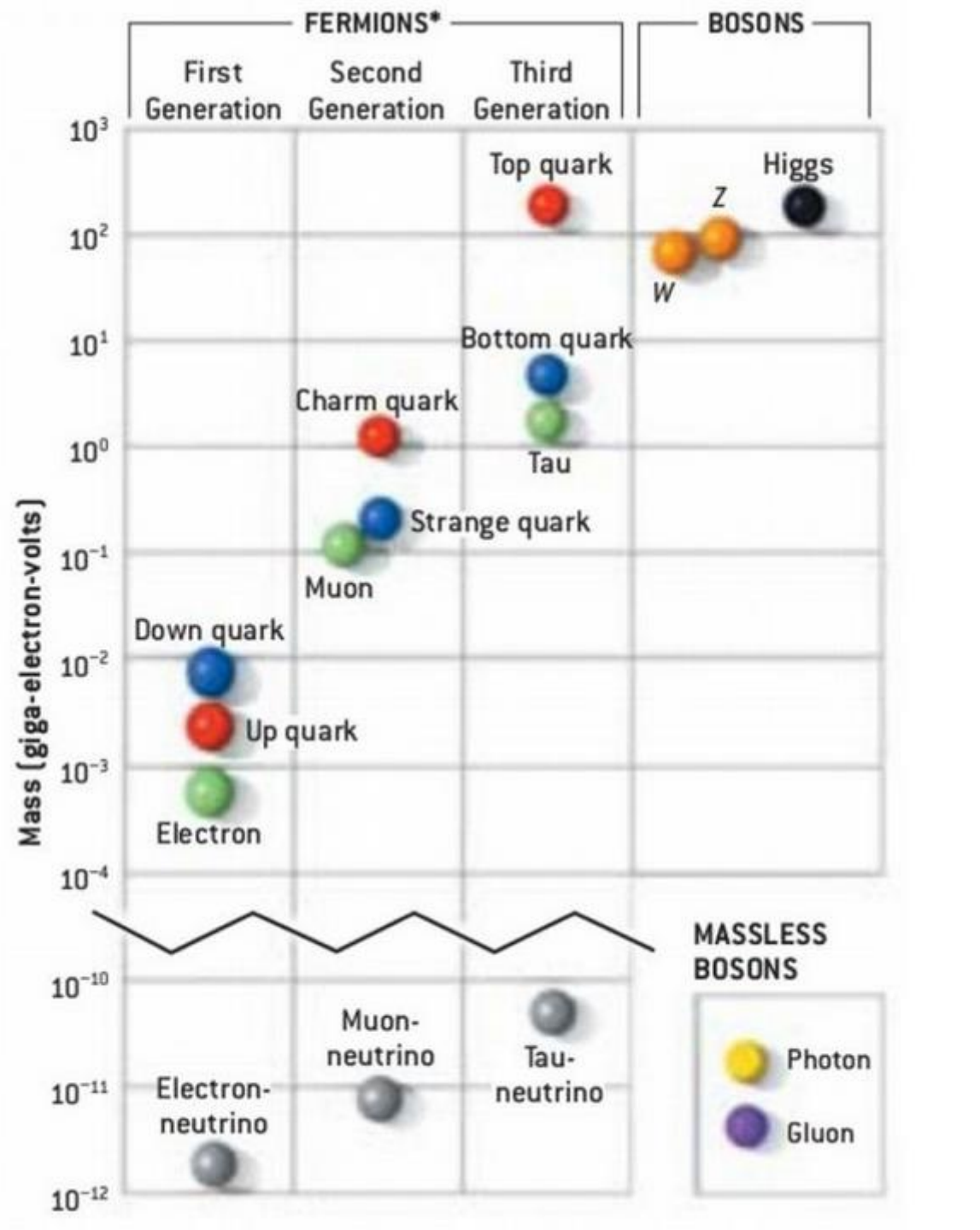
# 3 FAMILII (ASTĂZI!)




*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
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
Muon-neutrino
Tau-neutrino
Electron-neutrino
MASSLESS BOSONS
Photon
Gluon

număr asociat sarcinii electrice (Q)

număr barionic B

număr leptonic L ($L_e$, $L_\mu$, $L_\tau$)


| | Gravity | Weak (Electroweak) | Electromagnetic (Electroweak) | Strong |
|---|---|---|---|---|
| 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 electromagnetică** (particule cu sarcină electrică: cuarci, leptoni cu sarcină electrică)

**interacție tare** (cuarcii)

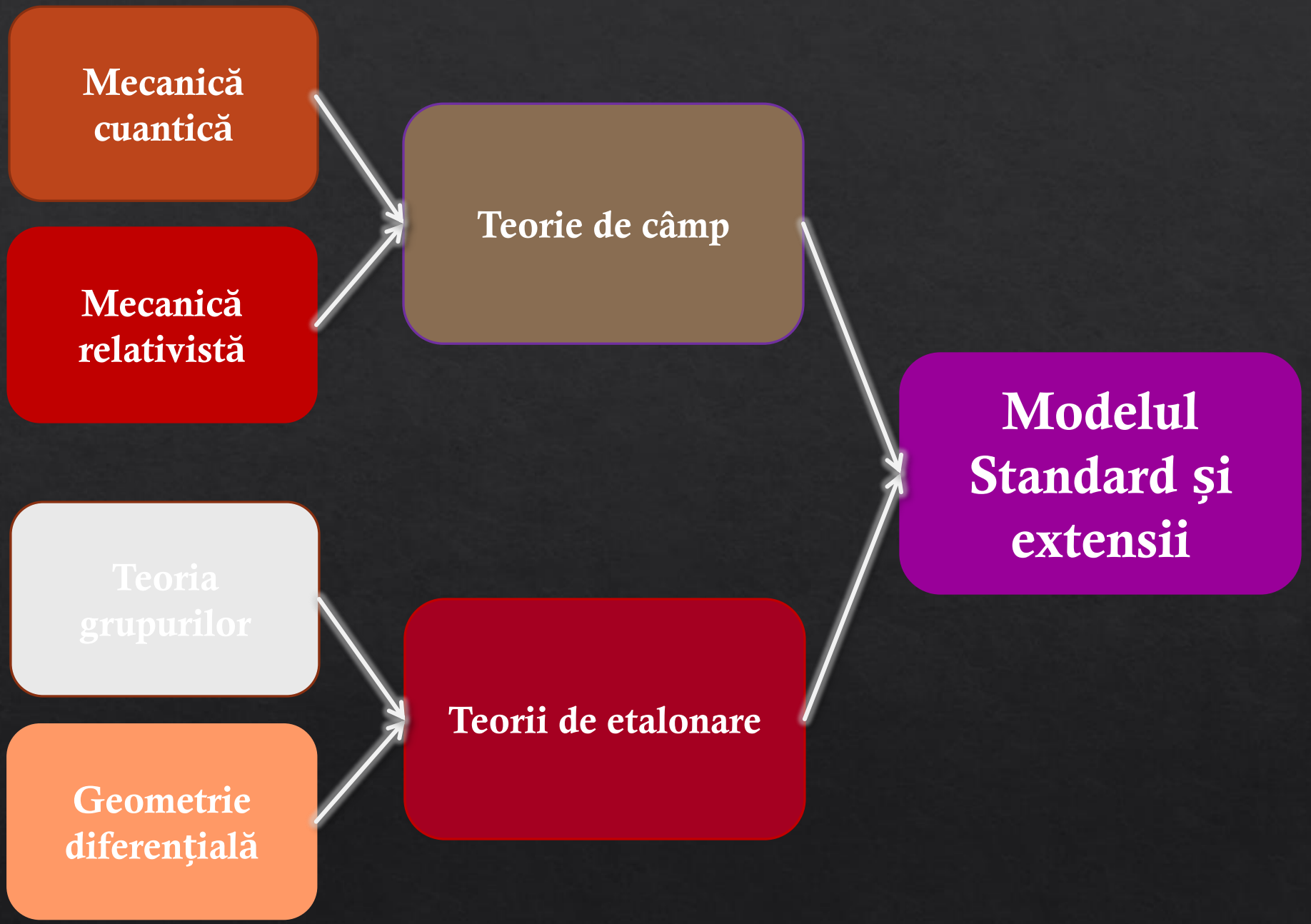
indiscernabilitatea particulelor identice

statistică cuantică

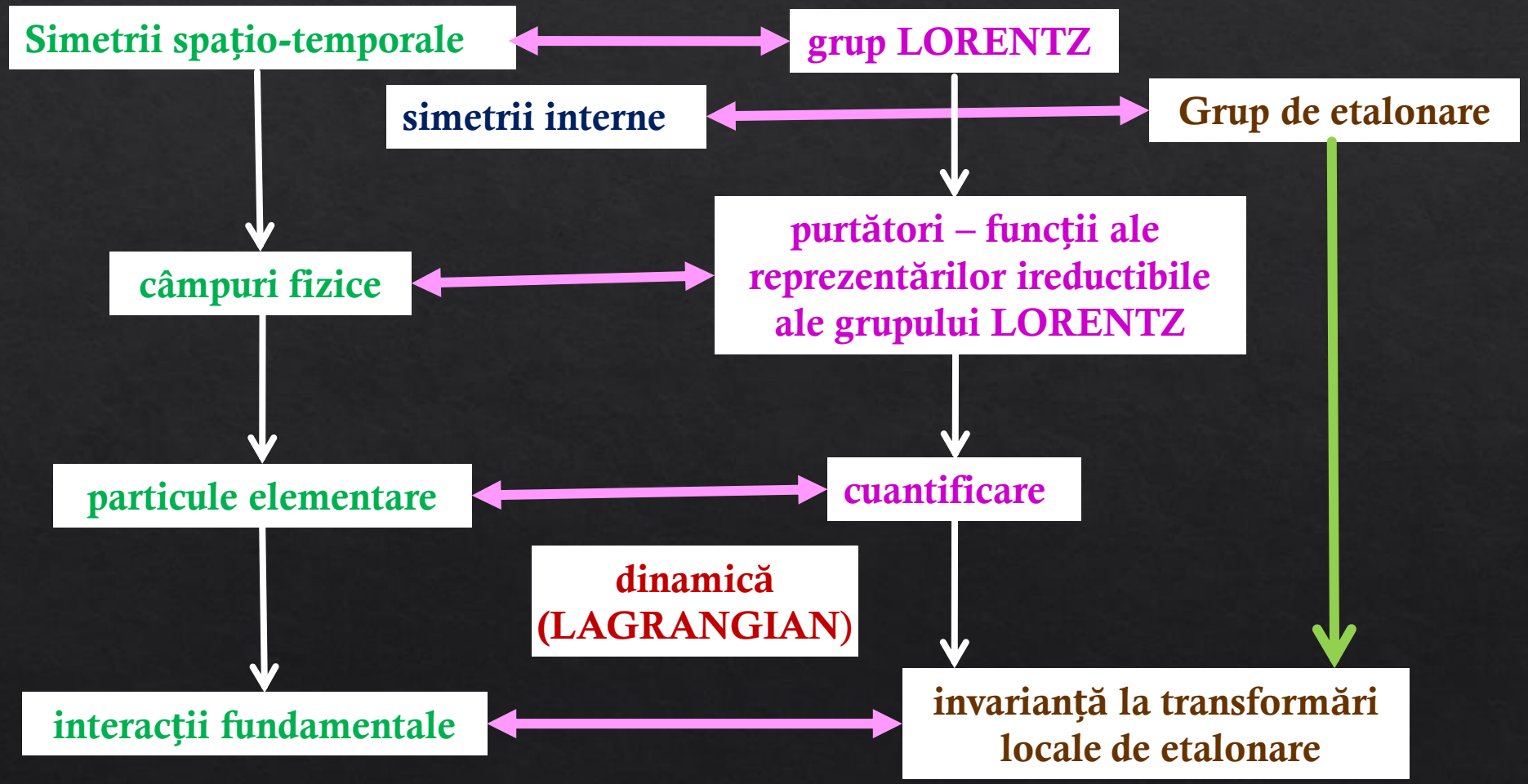
existența antiparticulelor

procese de creare și anihilare a particulelor

interacție cu schimb de particule


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

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



# Lagrangian – Glashow-Weinberg-Salam (interacție electro-slabă)

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

$$+\frac{g}{\sqrt{2}} \sum_i (\bar{a}_L^i \gamma^\mu b_L^i W_\mu^+ + \bar{b}_L^i \gamma^\mu a_L^i W_\mu^-) + \frac{g}{2c_w} \sum_f \bar{\Psi}_f \gamma^\mu (I_f^3 - 2s_w^2 Q_f - I_f^3 \gamma_5) \Psi_f Z_\mu +$$

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

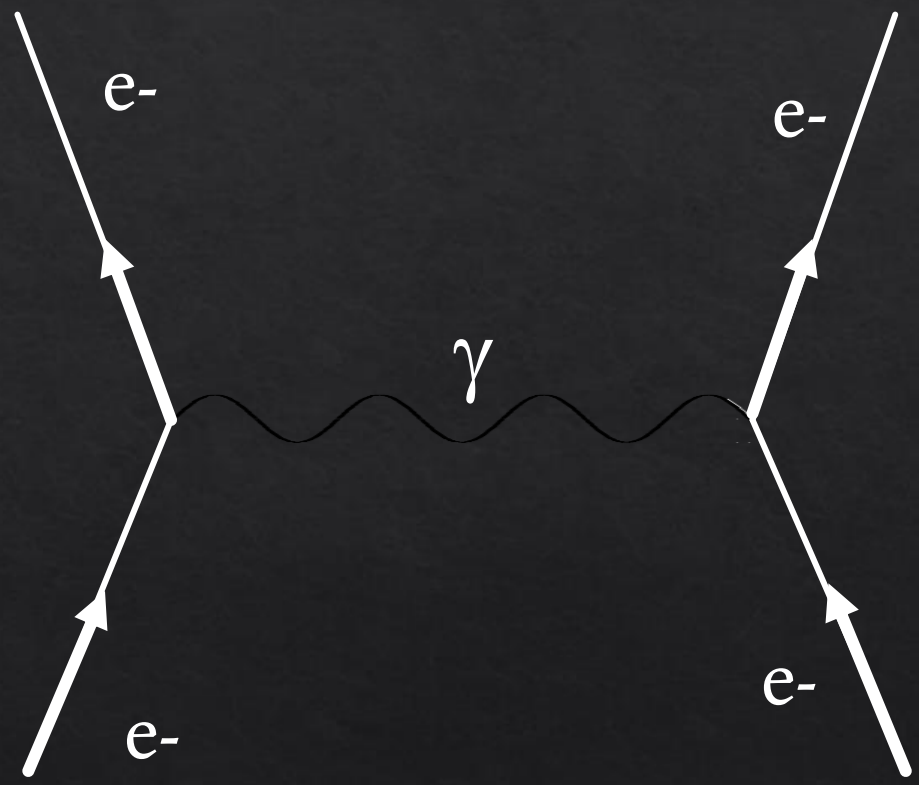
$$-ie(W_\mu^+ A_\nu - W_\nu^+ A_\mu) + ig' c_w (W_\mu^+ Z_\nu - W_\nu^+ Z_\mu|^2 +$$

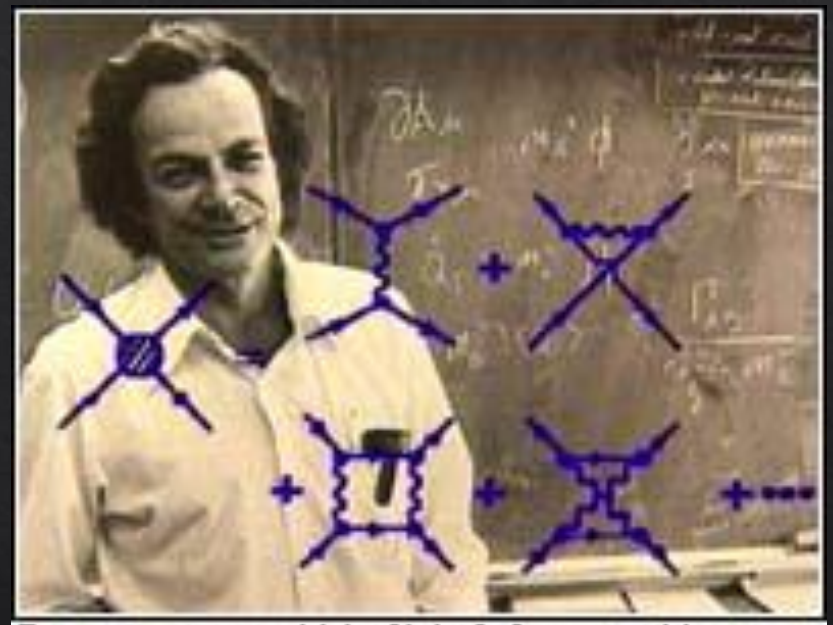
$$-\frac{1}{4}|\partial_\mu Z_\nu - \partial_\nu Z_\mu + ig' c_w (W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)|^2 +$$

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

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

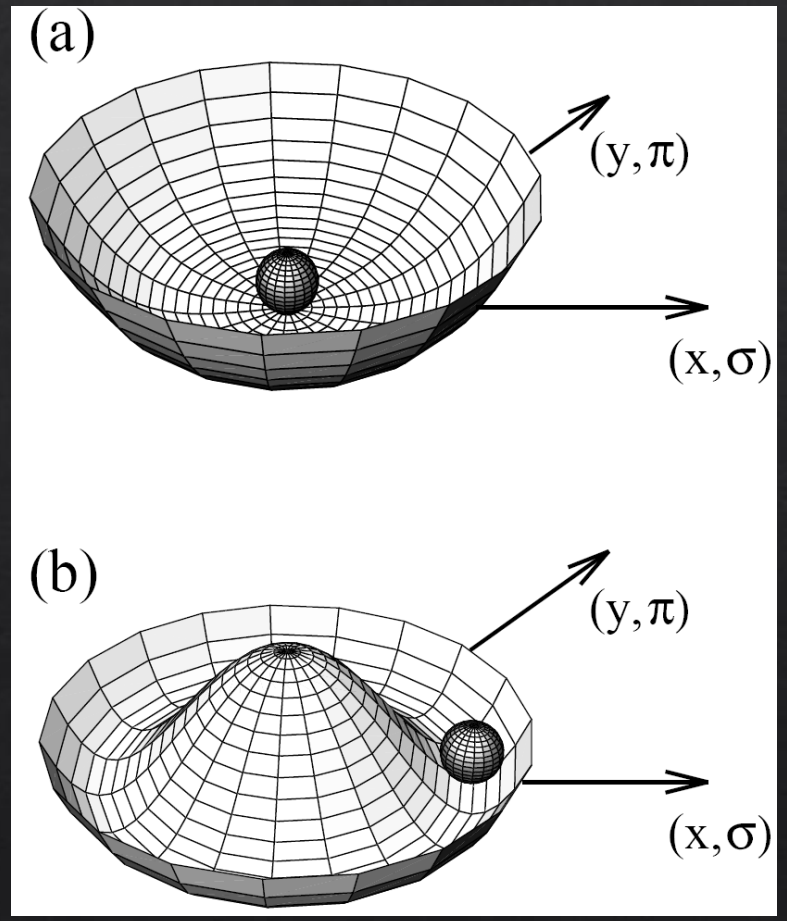
# Feynman – diagrame și reguli



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

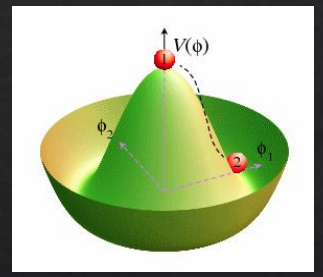
# De unde apare masa particulelor în teorie?



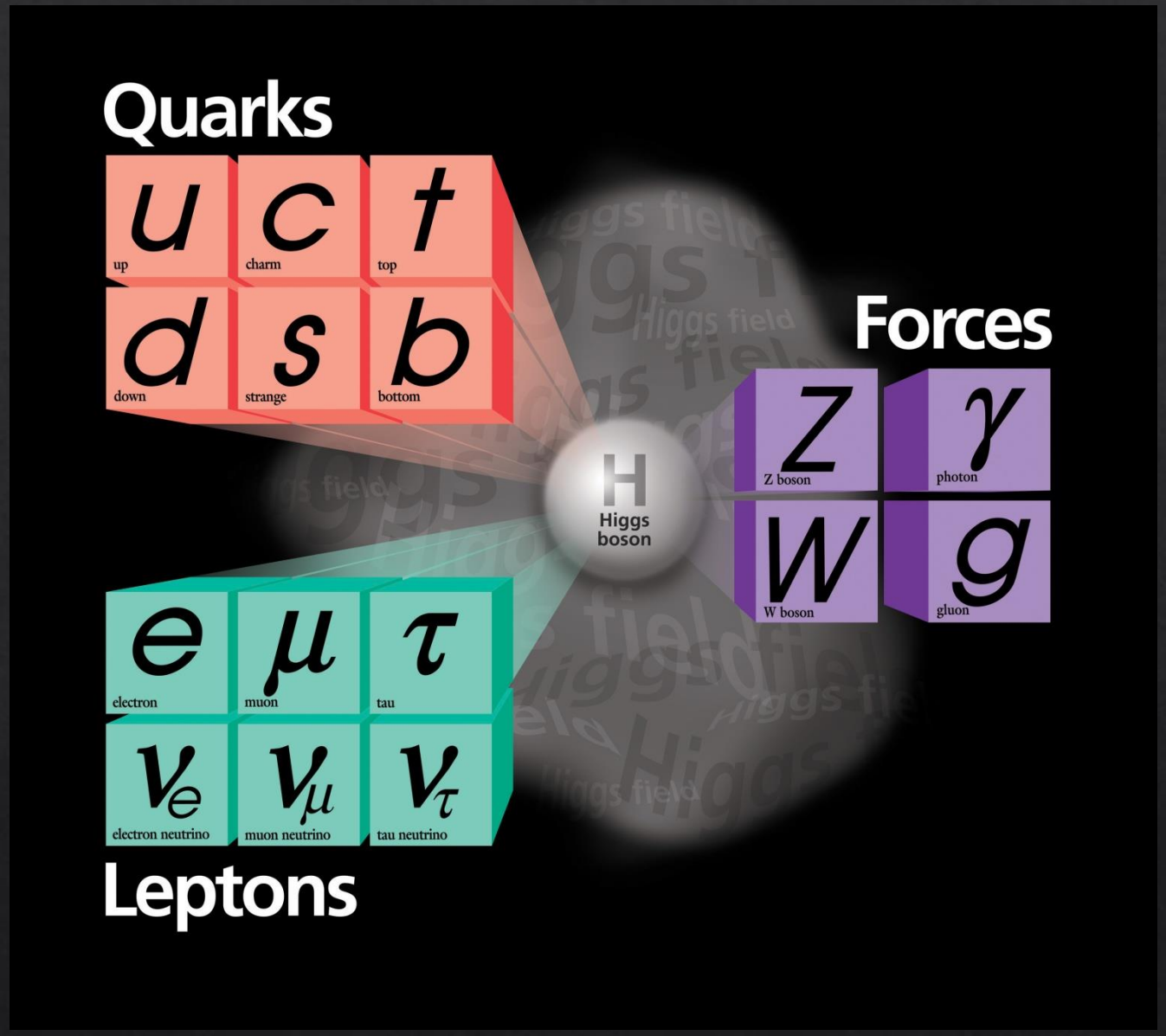

**$W^+$, $W^-$, Z – au masă**

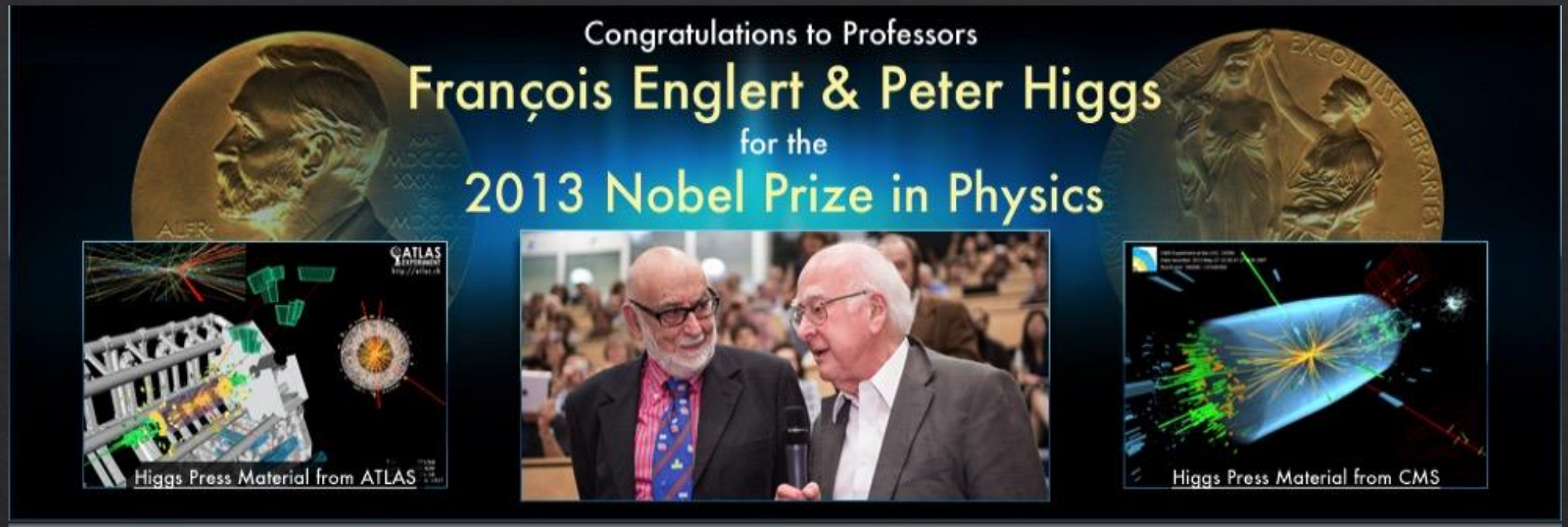
**- rezultă bozonul Higgs**

fără rupere spontană de simetrie




rupere spontană de simetrie

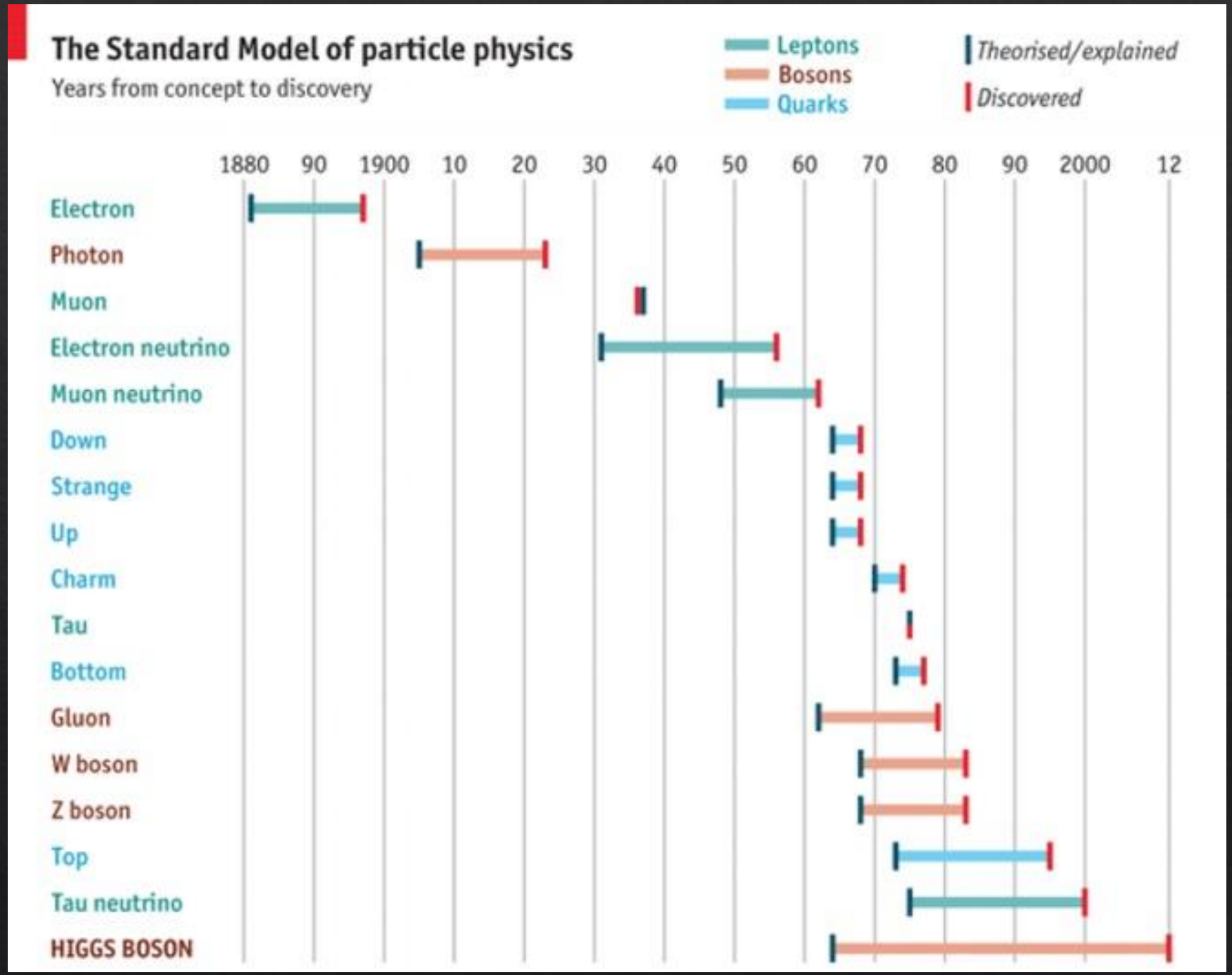

Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Higgs field
H
Higgs boson
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
Leptons



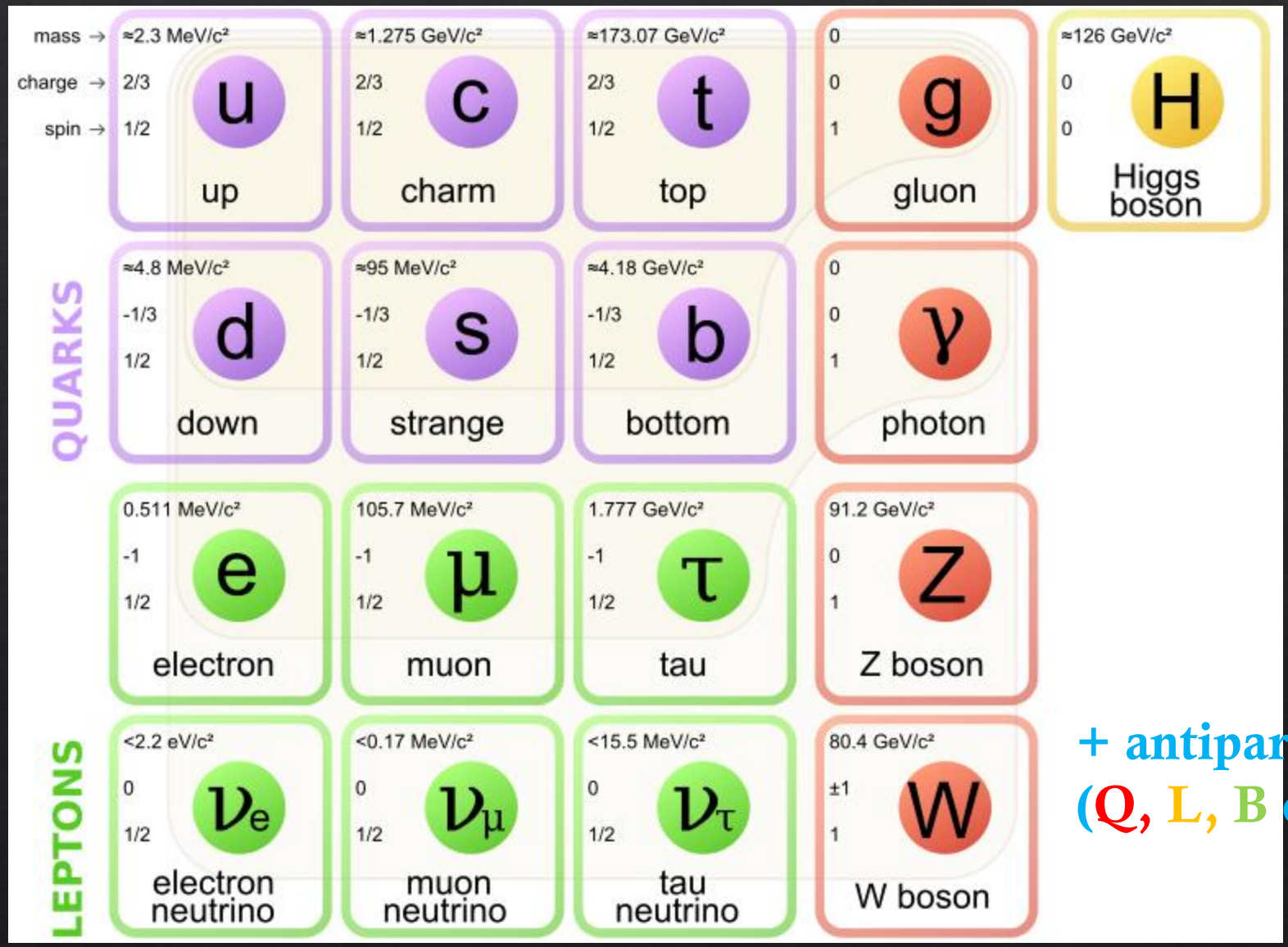

The ATLAS and CMS experiments at CERN congratulate Professors François Englert and Peter Higgs for their pioneering work in identifying the electro-weak-symmetry-breaking mechanism. CMS and ATLAS independently announced the discovery of a new particle on 4 July 2012, later identified as a Higgs boson, confirming the predictions of Professors Higgs, Englert and others in seminal papers published in 1964. We join in this celebration of the triumph of human curiosity and ingenuity.

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.

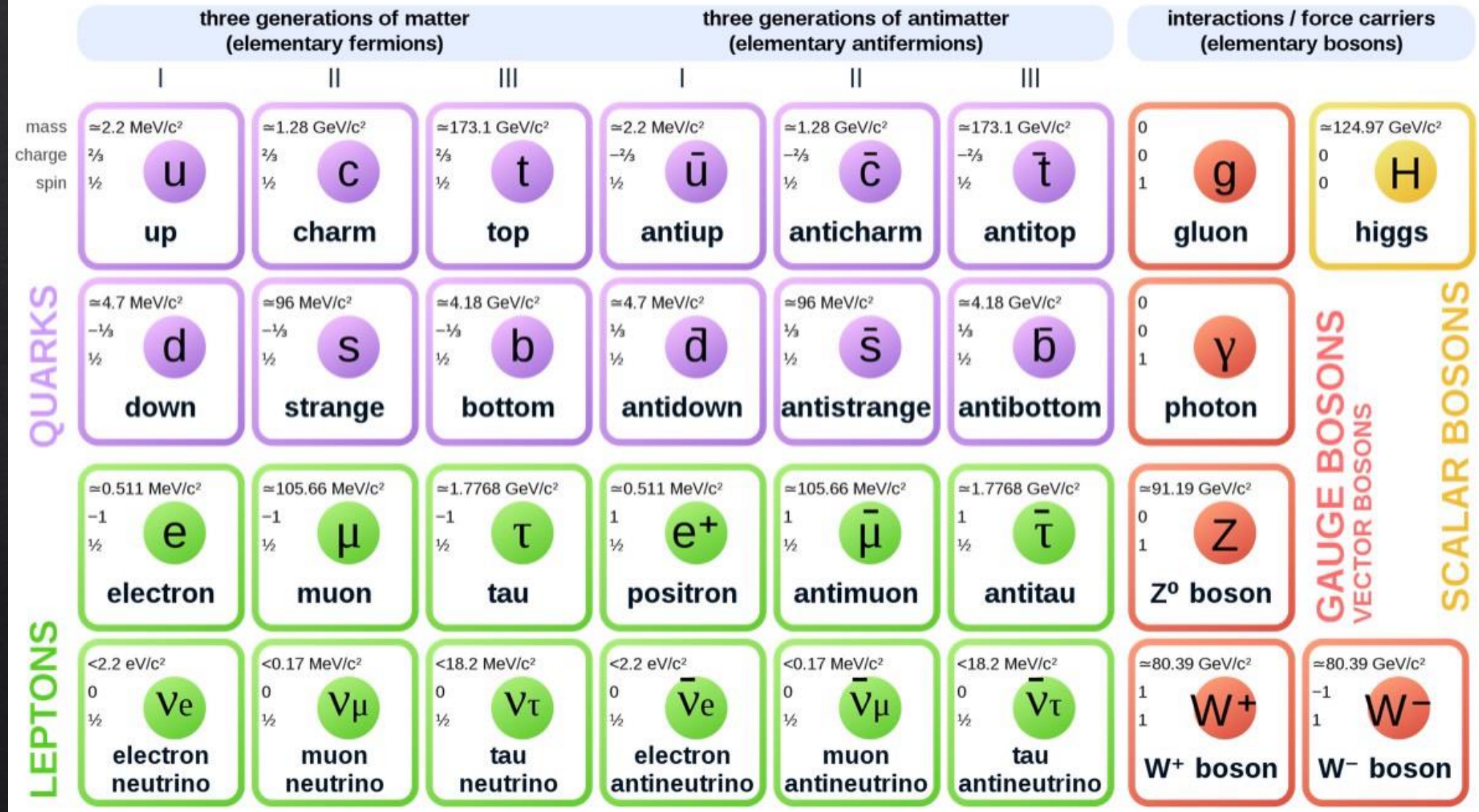

The Standard Model of particle physics
Years from concept to discovery
Leptons
Bosons
Quarks
Theorised/explained
Discovered
1880
90
1900
10
20
30
40
50
60
70
80
90
2000
12
Electron
Photon
Muon
Electron neutrino
Muon neutrino
Down
Strange
Up
Charm
Tau
Bottom
Gluon
W boson
Z boson
Top
Tau neutrino
HIGGS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

# Modelul Standard



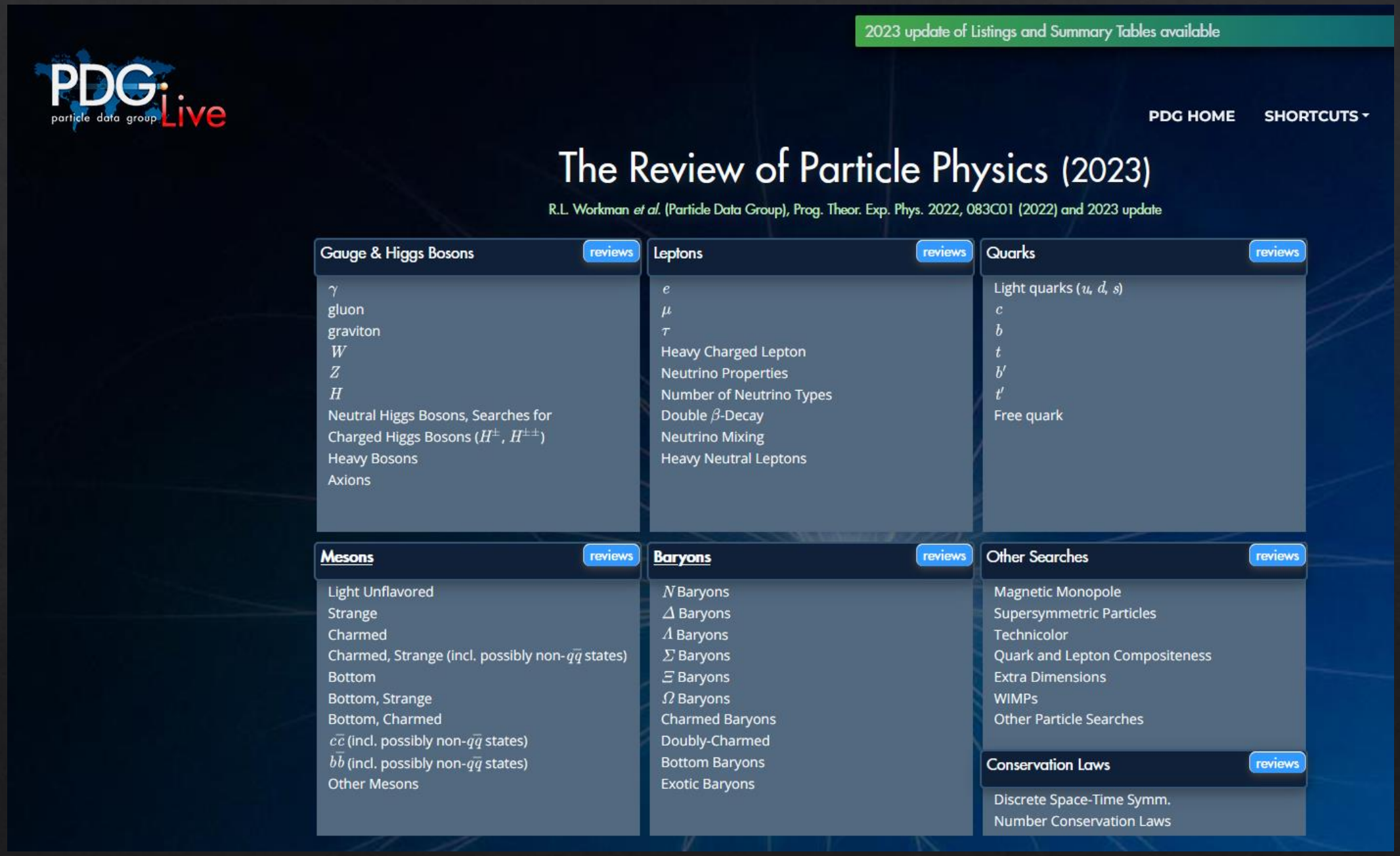

+ antiparticule
(Q, L, B opus)!

# Standard Model of Elementary Particles



# 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?




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)[‡] | exact |
| Planck constant, reduced | $\hbar = h/2\pi$ | $1.054\ 571\ 817\ldots\times10^{-34}$ 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... MeV fm | exact* |
| conversion constant | $(\hbar c)^2$ | 0.389 379 372 1... $GeV^2$ 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** | $u$ = (mass $^{12}$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 | $\alpha = e^2/4\pi\epsilon_0\hbar c$ | $7.297\ 352\ 5693(11)\times10^{-3} = 1/137.035\ 999\ 084(21)$[†] | 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 | $1.9\times10^{-3}$ |
| 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$^{-2}$ | $2.2\times10^4$ |
| | | $= 6.708\ 83(15)\times10^{-39}\ \hbar c$ (GeV/$c^2$)$^{-2}$ | $2.2\times10^4$ |
| 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 | $\sigma = \pi^2 k^4/60\hbar^3 c^2$ | $5.670\ 374\ 419\ldots\times10^{-8}$ 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 | $\sin^2\widehat{\theta}(M_Z)$ ($\overline{\rm MS}$) | 0.231 22(4)†† | $1.7\times10^5$ |
| $W^\pm$ boson mass | $m_W$ | 80.379(12) GeV/$c^2$ | $1.5\times10^5$ |
| $Z^0$ boson mass | $m_Z$ | 91.1876(21) GeV/$c^2$ | $2.3\times10^4$ |
| strong coupling constant | $\alpha_s(m_Z)$ | 0.1179(10) | $8.5\times10^6$ |

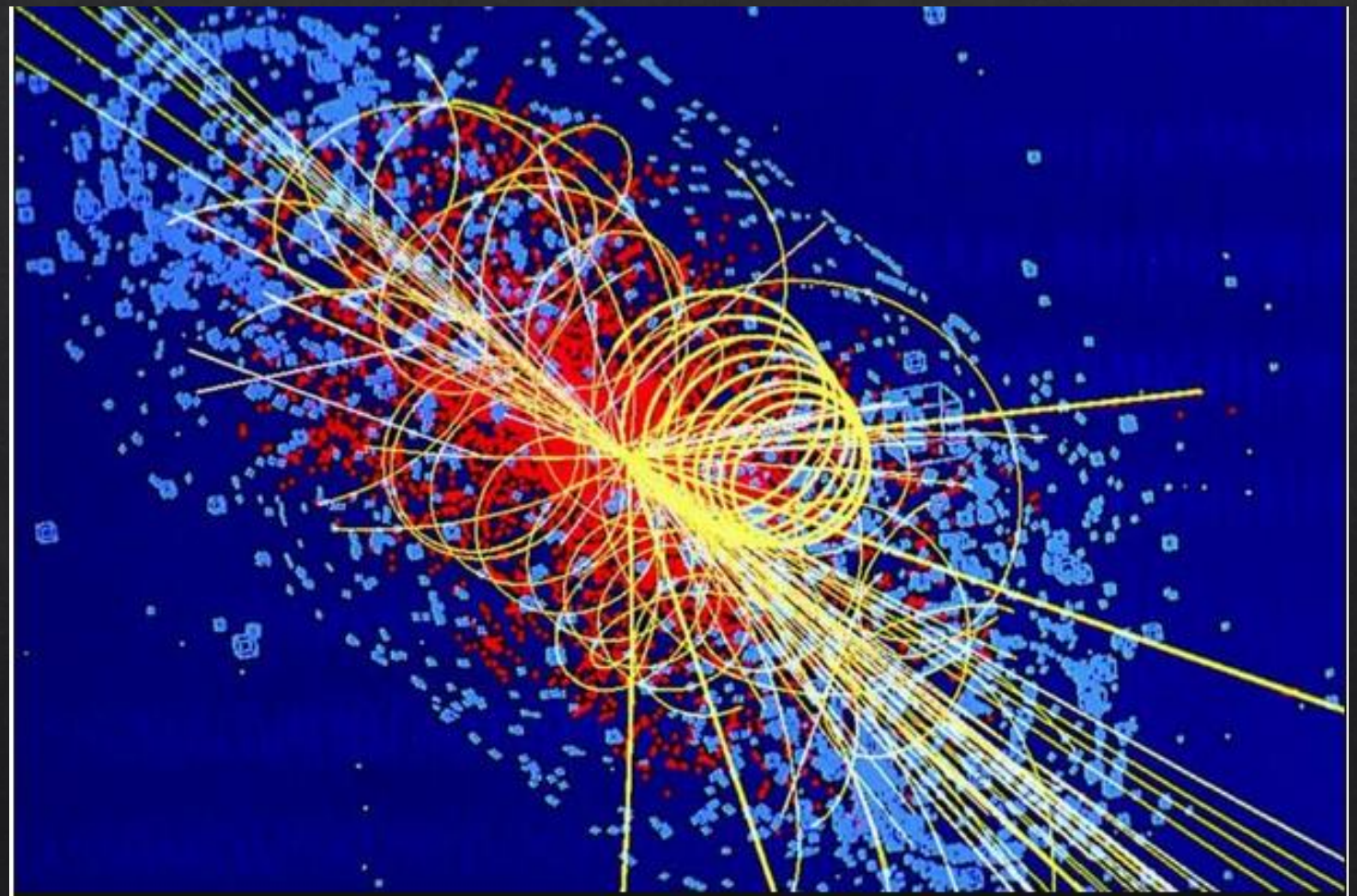
$\pi = 3.141\ 592\ 653\ 589\ 793\ 238\ldots$ $e = 2.718\ 281\ 828\ 459\ 045\ 235\ldots$ $\gamma = 0.577\ 215\ 664\ 901\ 532\ 860\ldots$

| | | | |
|---|---|---|---|
| 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 | $(1\text{ kg})c^2 = 5.609\ 588\ 603\ldots\times10^{35}$ 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 $\nu$ 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 $\sigma_{fi}$
ciocniri: secțiune eficace de împrăștiere

$$= \frac{W_{fi}}{(initial\ \ flux)} (number\ of\ \ \ final\ states)$$

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

M – amplitudine de tranziție

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

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?

$$-\frac{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 - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{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 - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h [\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{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)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac{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^-] - \frac{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)^2 H^2] - gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \frac{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)] + \frac{1}{2}g[W^+_\mu (H\partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H\partial_\mu \phi^+ - \phi^+ \partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig\frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w MA_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) - ig\frac{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^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] - \frac{1}{4}g^2 \frac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{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^\lambda_e) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + igs_w A_\mu [-(\bar{e}^\lambda \gamma e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j \gamma u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j \gamma d^\lambda_j)] + \frac{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 (\frac{4}{3}s_w^2 - 1 - \gamma^5) u^\lambda_j) + (\bar{d}^\lambda_j \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d^\lambda_j)] + \frac{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)] + \frac{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)] + \frac{ig}{2\sqrt{2}} \frac{m^\lambda_e}{M} [-\phi^+ (\bar{\nu}^\lambda (1 - \gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1 + \gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m^\lambda_e}{M} [H(\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}} \phi^+ [-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1 - \gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1 + \gamma^5) d^\kappa_j] + \frac{ig}{2M\sqrt{2}} \phi^- [m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 + \gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1 - \gamma^5) u^\kappa_j] - \frac{g}{2} \frac{m^\lambda_u}{M} H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2} \frac{m^\lambda_d}{M} H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2} \frac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \frac{ig}{2} \frac{m^\lambda_d}{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 - \frac{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^-) - \frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w^2} \bar{X}^0 X^0 H] + \frac{1-2c_w^2}{2c_w} igM[\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-] + \frac{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^-] + \frac{1}{2}igM[\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]$$


interacția particulelor

interacția dintre particule asociate materiei

masa particulelor asociate materiei

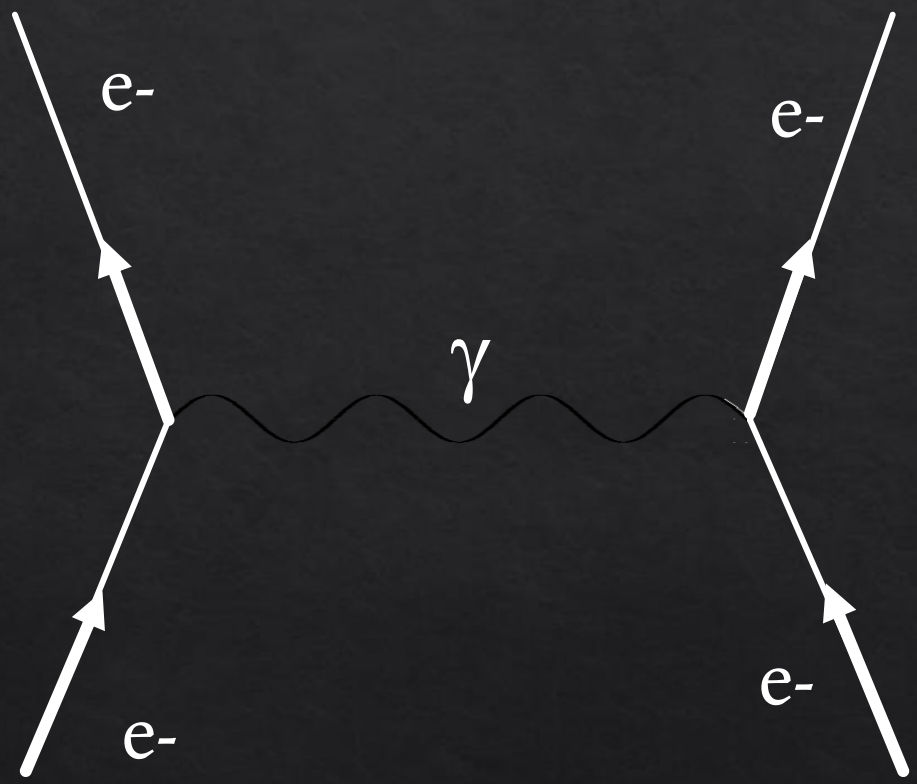
masa anti-particulelor

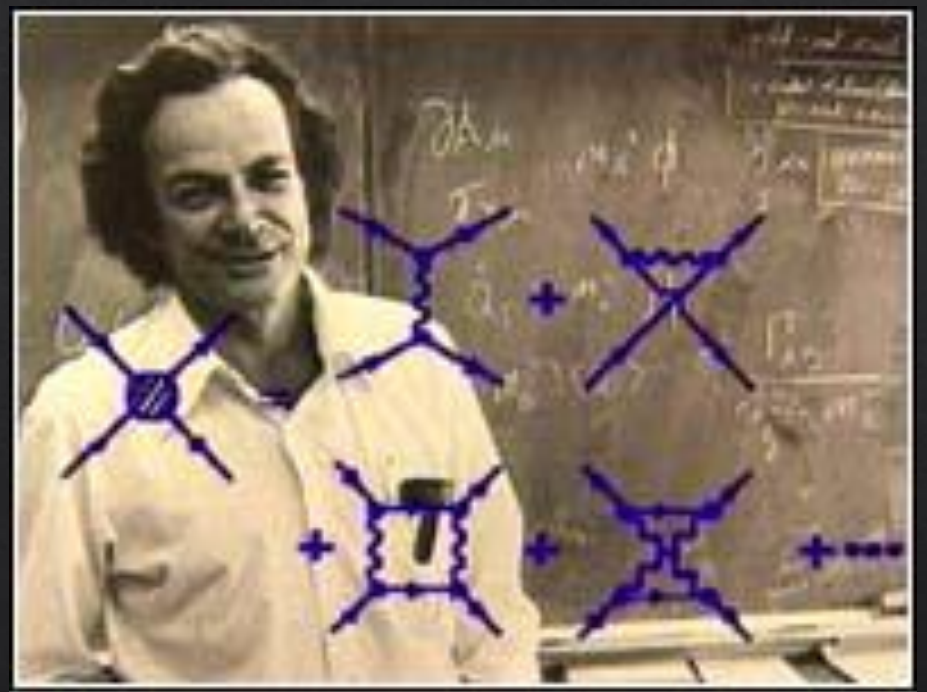
Higgs – interacții

masa particulelor care mediază interacțiile

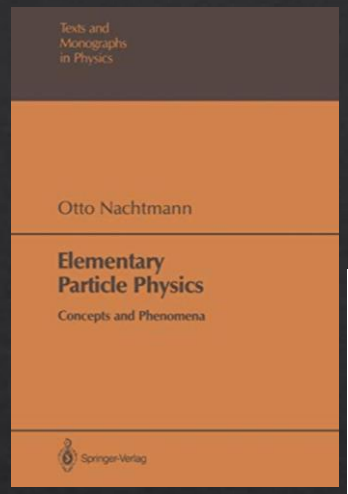
https://home.cern/news/news/cern/sit-down-coffee-standard-model

# Feynman – diagrame și reguli

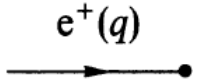
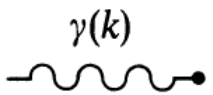


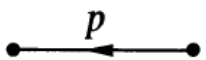



Feynman earned his Nobel for creating these diagrams
(Courtesy Auckland University)




# Feynman – diagrame și reguli
# Electrodinamică cuantică

| | |
|---|---|
| electron in initial state | incoming electron line |
| $u(p)$ | $e^-(p)$  |
| electron in final state | outgoing electron line |
| $\bar{u}(p)$ | $e^-(p)$  |
| positron in initial state | outgoing electron line |
| $\bar{v}(q)$ | $e^+(q)$  |
| positron in final state | incoming electron line |
| $v(q)$ | $e^+(q)$  |
| photon in initial state | incoming photon line |
| $\varepsilon^\mu$ | $\gamma(k)$  |

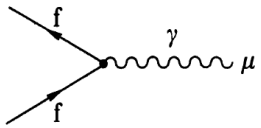
| | |
|---|---|
| photon in final state | outgoing photon line |
| $\varepsilon^{\mu *}$ | $\gamma(k)$  |
| virtual photon | internal photon line |
| $\frac{-ig_{\mu\nu}}{k^2 + i\varepsilon}$ | $k$  $\mu$ $\nu$ |
| virtual electron | internal electron line |
| $i\frac{\not{p} + m}{p^2 - m^2 + i\varepsilon}$ | $p$  |
| elementary process | vertex |
| $ie\gamma^\mu$ |  |

# Feynman – diagrame și reguli

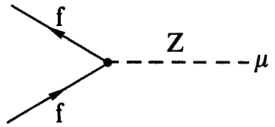
| | |
|---|---|
| $W^-$ initial state | incoming W line |
| $\varepsilon(k)$ | $W^-(k)$ |
| $W^-$ in final state | outgoing W line |
| $\varepsilon^*(k)$ | $W^-(k)$ |
| $W^+$ in initial state | outgoing W line |
| $\varepsilon(k)$ | $W^+(k)$ |
| $W^+$ in final state | incoming W line |
| $\varepsilon^*(k)$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

Fermion–Boson vertices:

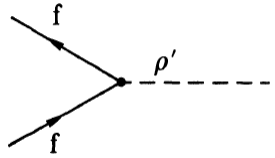
$-ieQ_f\gamma^\mu$



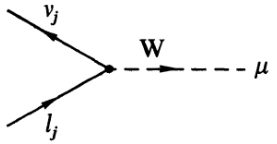

$$-i\frac{e}{\sin\vartheta_W\cos\vartheta_W}\left\{T_3^f\gamma^\mu\frac{1-\gamma_5}{2}-\sin^2\vartheta_W Q_f\gamma^\mu\right\}$$



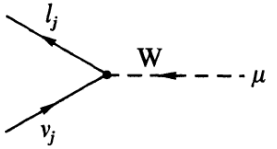

$$-i\frac{m_f}{\rho_0}$$



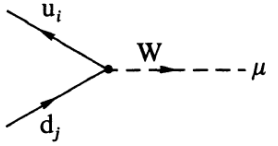

$$-i\frac{e}{\sqrt{2}\sin\vartheta_W}\gamma^\mu\frac{1-\gamma_5}{2}$$



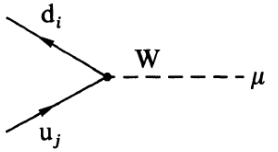

$$-i\frac{e}{\sqrt{2}\sin\vartheta_W}\gamma^\mu\frac{1-\gamma_5}{2}$$




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

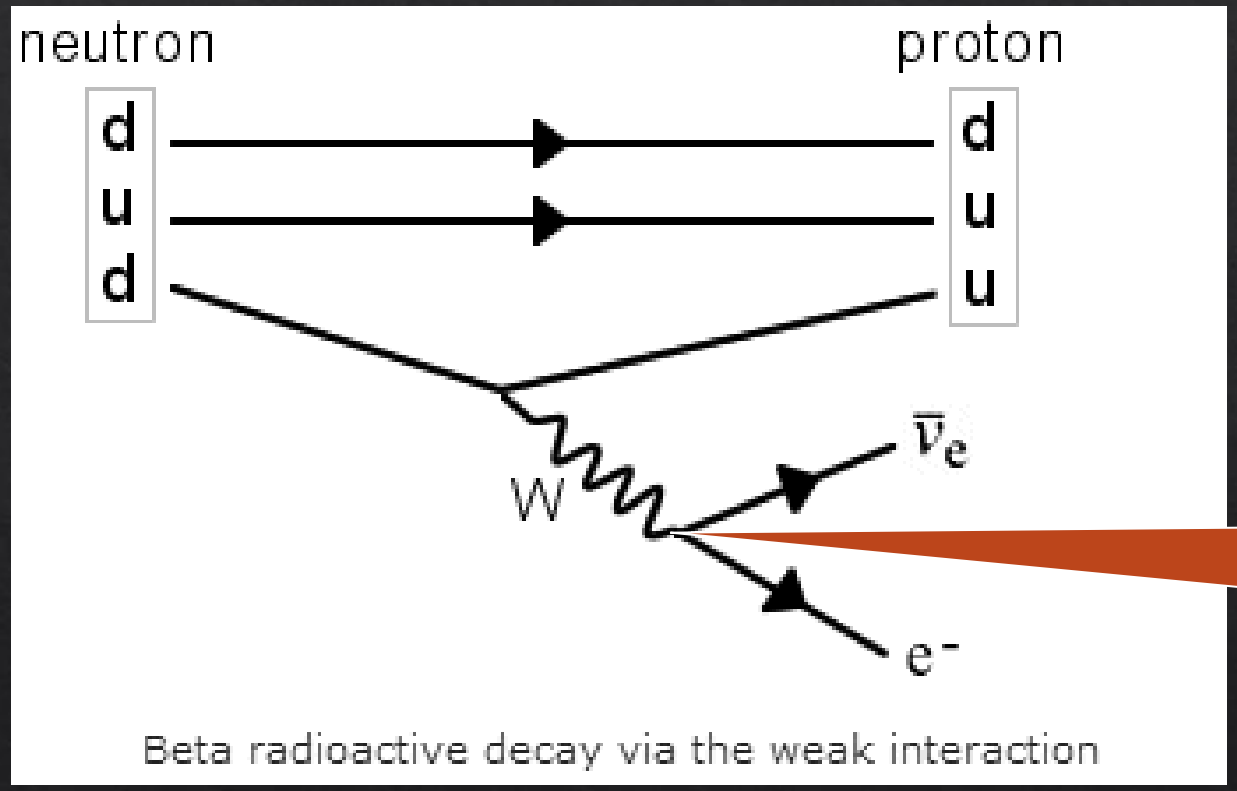



$$-i\frac{e}{\sqrt{2}\sin\vartheta_W}V_{ji}^*\gamma^\mu\frac{1-\gamma_5}{2}$$




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

# Feynman – diagrame și reguli

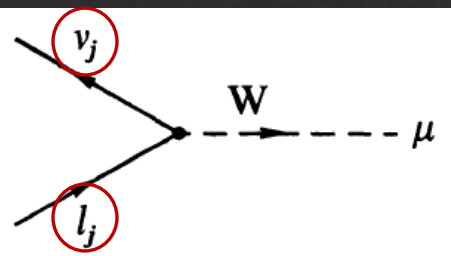



Beta radioactive decay via the weak interaction

Sarcina electrică se conservă la fiecare vertex

# Feynman – diagrame și reguli

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



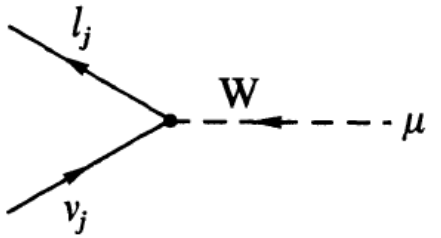

$$-i\frac{e}{\sqrt{2}\sin\vartheta_W}\gamma^\mu\frac{1-\gamma_5}{2}$$

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

$\ell_1 \equiv$ e, $\ell_2 \equiv \mu$, $\ell_3 \equiv \tau$;

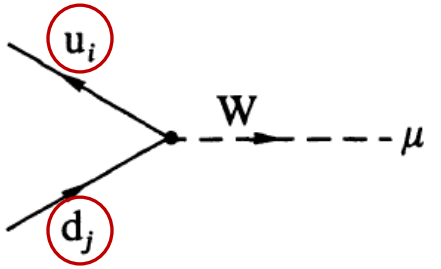
$u_1 \equiv$ u, $u_2 \equiv$ c, $u_3 \equiv$ t;

$d_1 \equiv$ d, $d_2 \equiv$ s, $d_3 \equiv$ b.

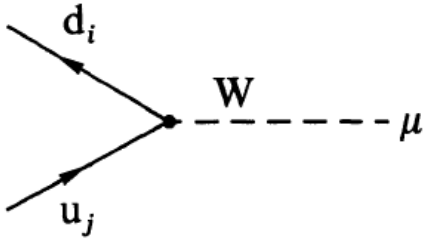



$$-i\frac{e}{\sqrt{2}\sin\vartheta_W}V_{ij}\gamma^\mu\frac{1-\gamma_5}{2}$$

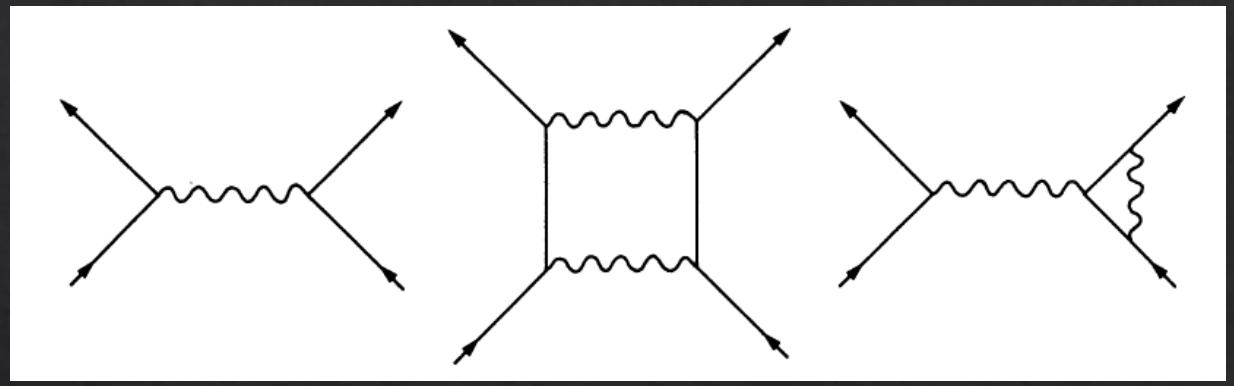
matricea de mixing a cuarcilor
(Cabibbo–Kobayashi–Maskawa)

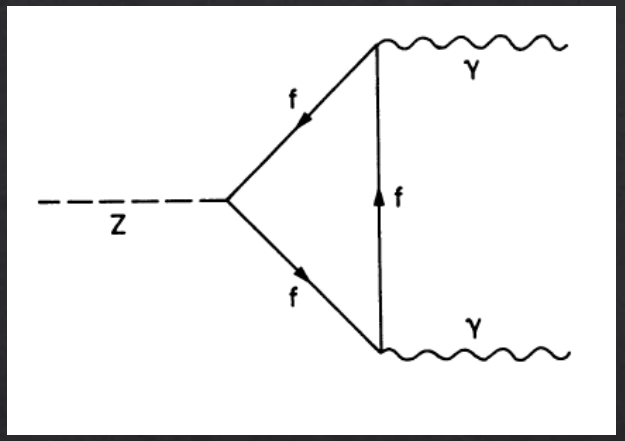


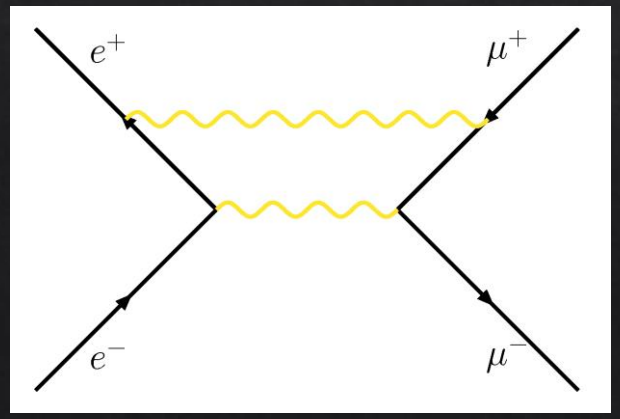

$$-i\frac{e}{\sqrt{2}\sin\vartheta_W}V_{ji}^*\gamma^\mu\frac{1-\gamma_5}{2}$$

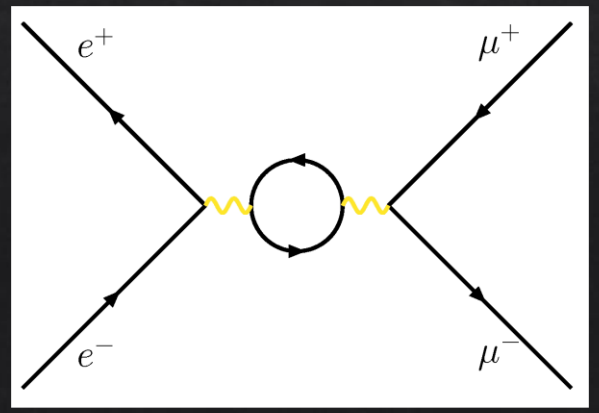


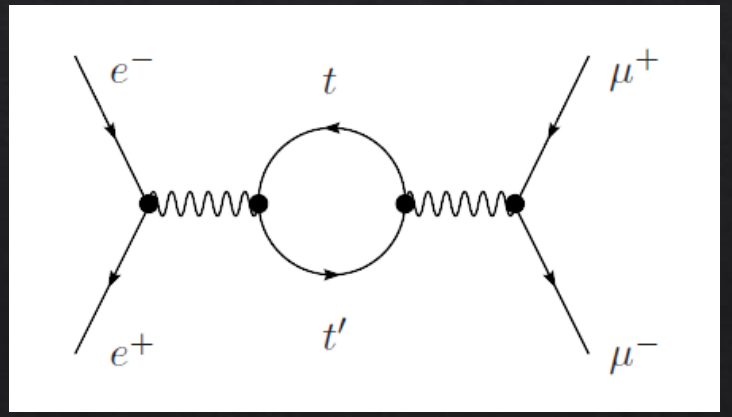
# …și mai multe!
# Teoria perturbațiilor – corecții



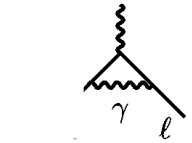


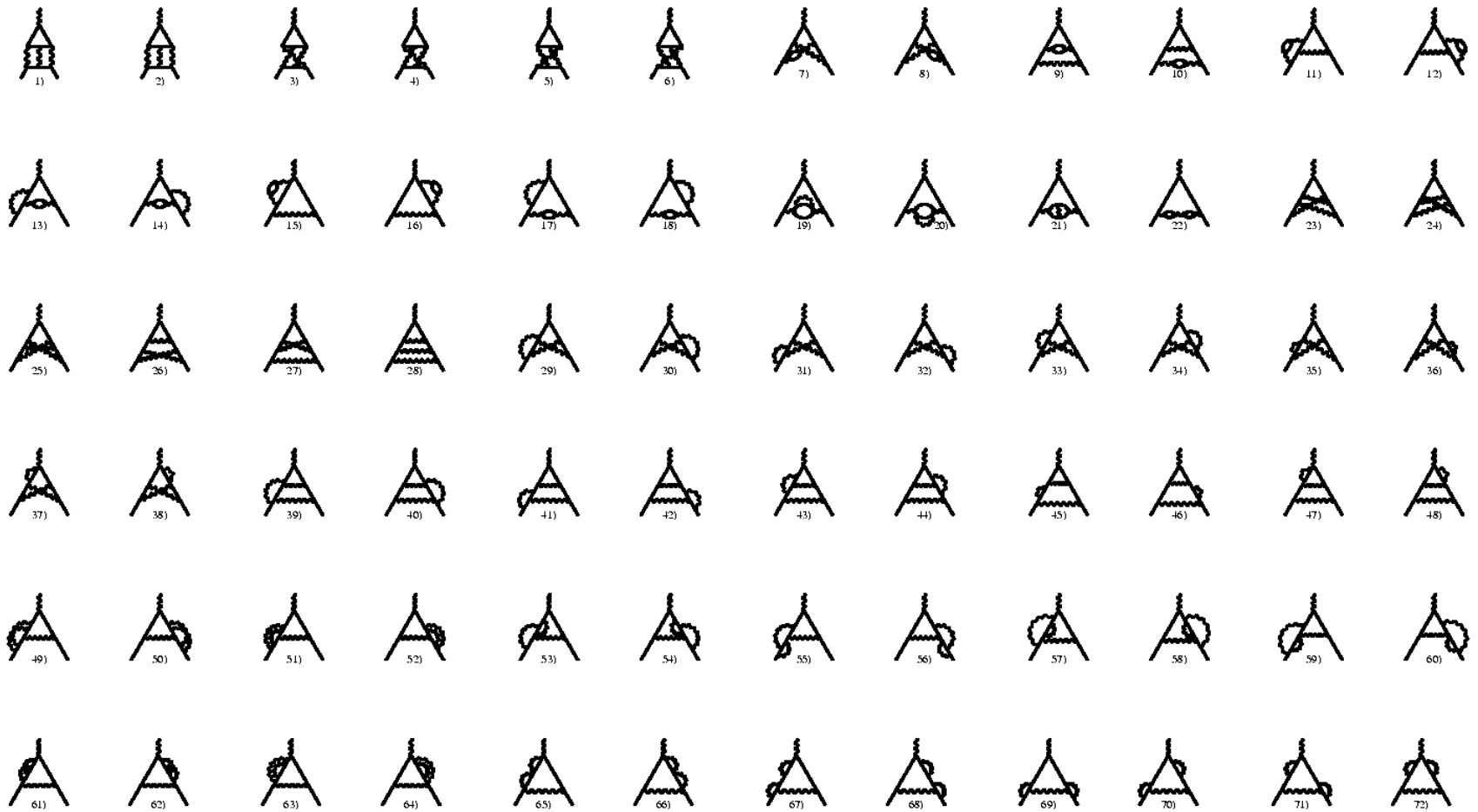



$(g\text{-}2)_\ell$ $\ell$=e,μ,τ




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



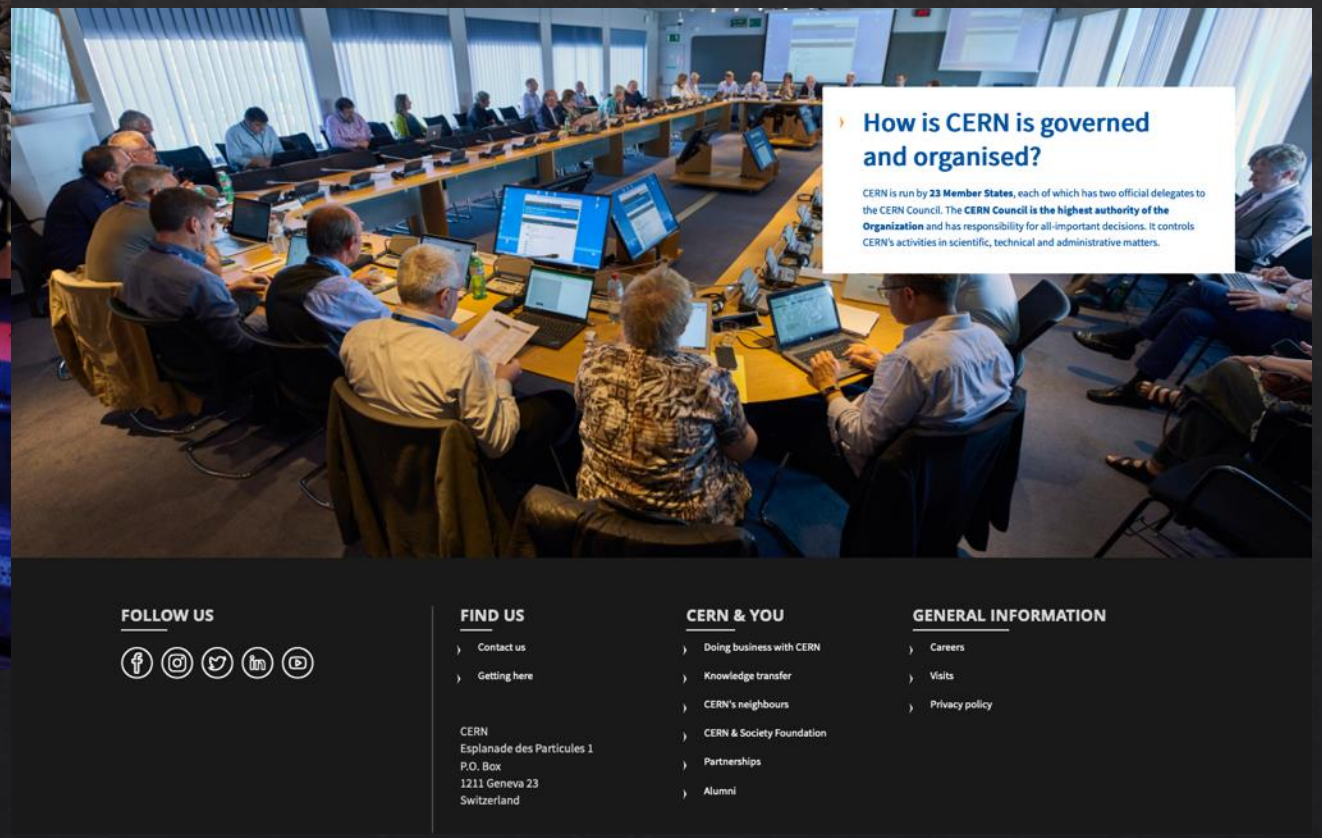
# 3. Cum producem particule elementare?

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

# Accelerating Science and Innovation

CERN

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

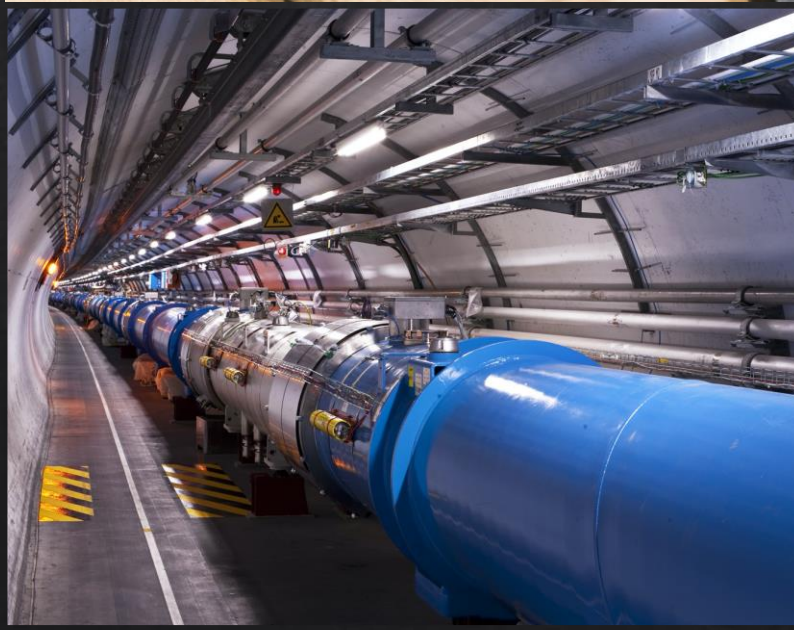
| Experiments | WLCG participation |
|---|---|
| ALICE , ATLAS , LHCb , DIRAC , ISOLDE , NA62 , CLICdp | Tier 2 |

## 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

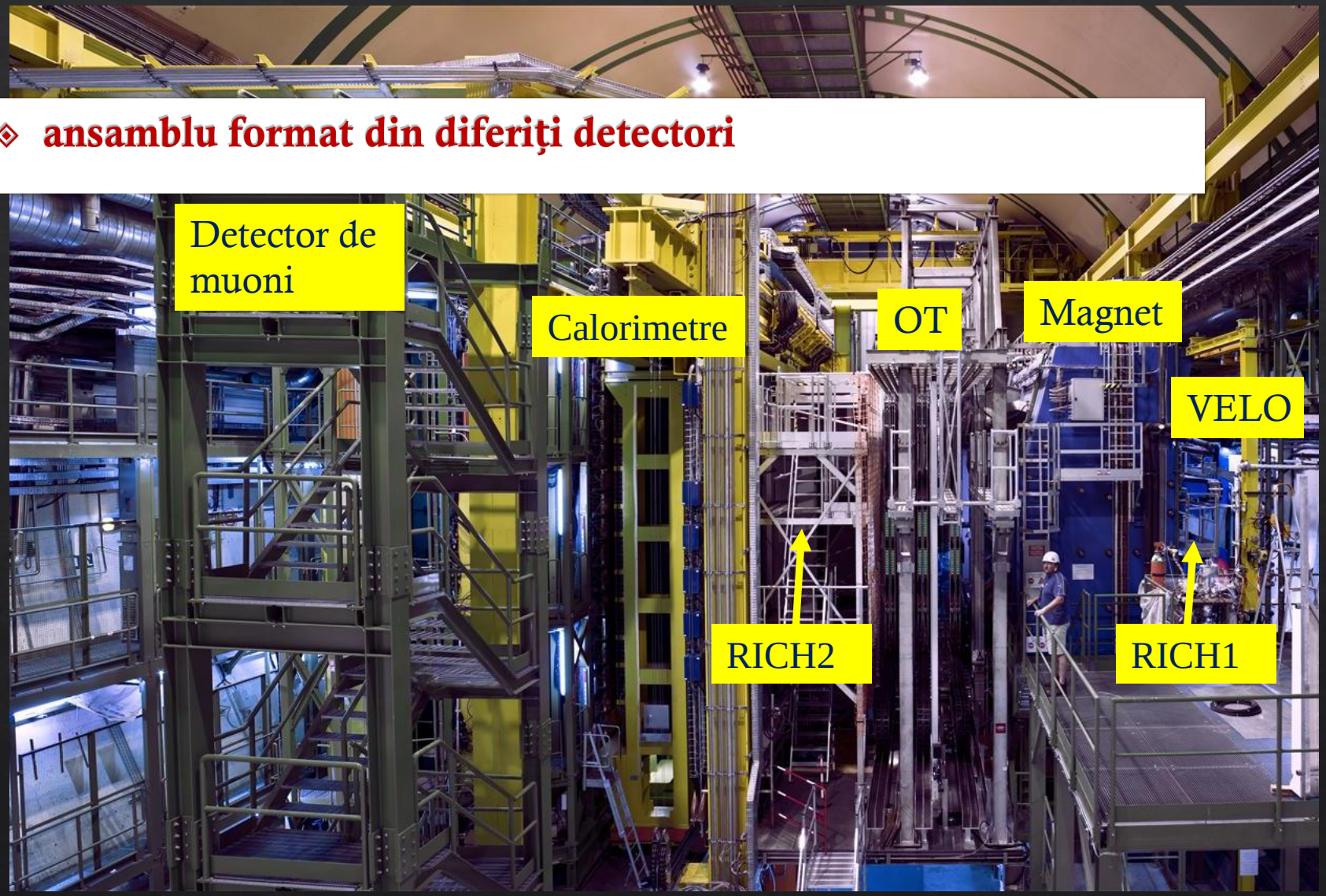



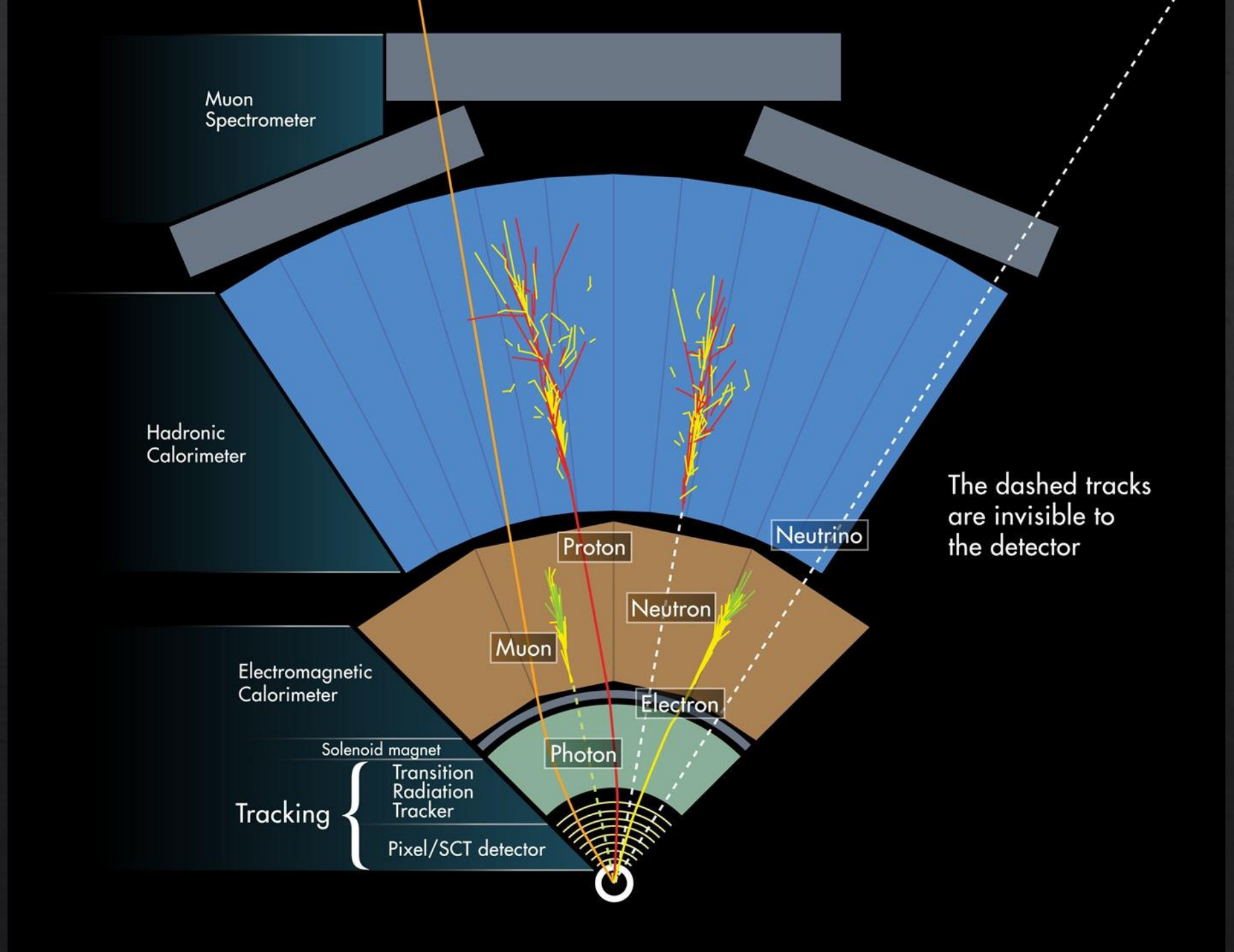
# Proiecte in derulare

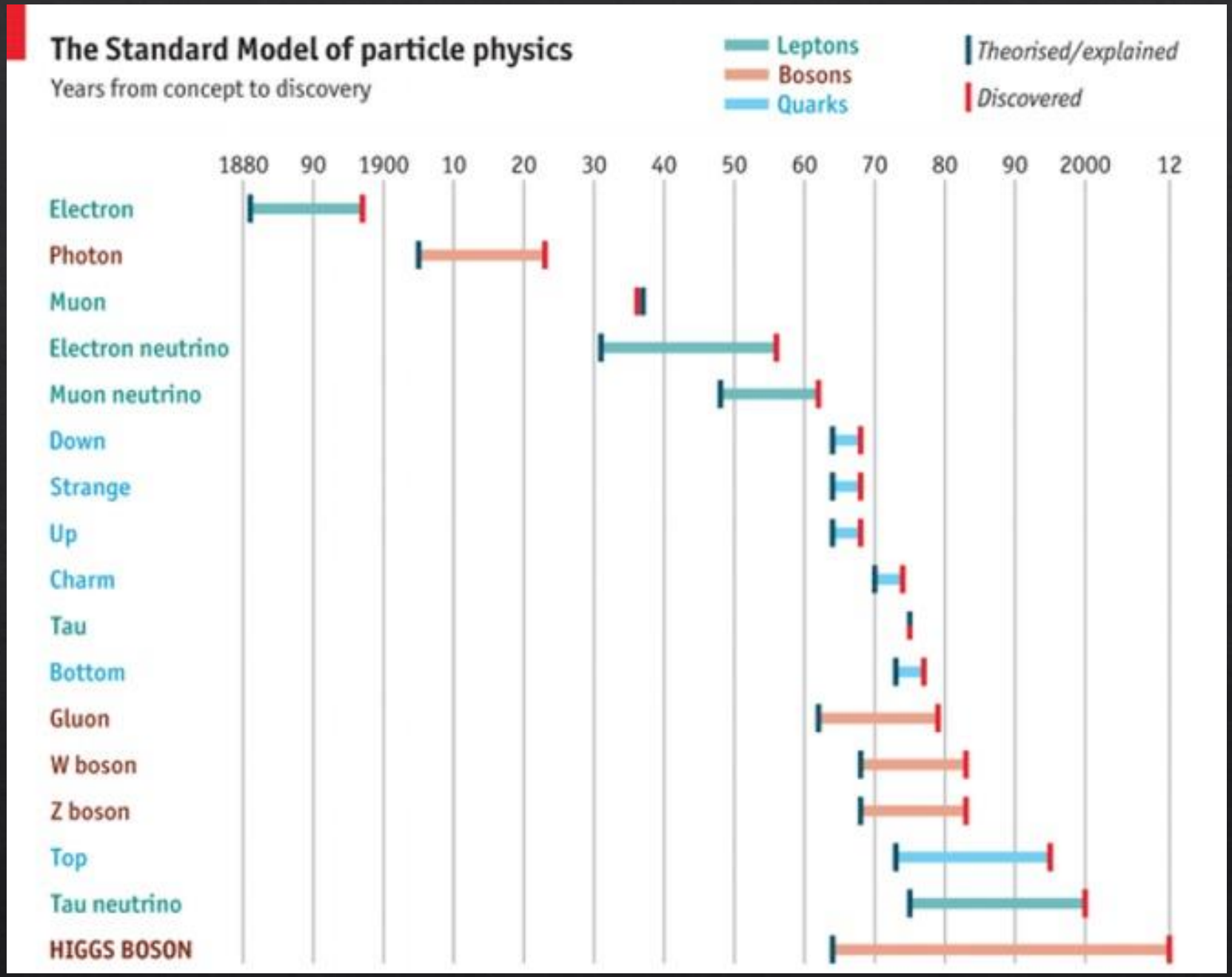
| Experiment | Conducator proiect(CO )/ Parteneri | Director proiect |
|---|---|---|
| ALICE | CO: IFIN-HH | Mihai PETROVICI<br>mpetro@ifin.nipne.ro |
| | CO: ISS | Alexandru Florin DOBRIN<br>alexandru.florin.dobrin@cern.ch |
| ATLAS EXPERIMENT and RD51 | CO: IFIN-HH | Calin ALEXA<br>calin.alexa@cern.ch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

# 4. Cum detectăm particule elementare?

- **ansamblu format din diferiţi detectori**




Muon
Spectrometer
Hadronic
Calorimeter
Electromagnetic
Calorimeter
Solenoid magnet
Tracking
Transition
Radiation
Tracker
Pixel/SCT detector
Proton
Neutrino
Neutron
Muon
Electron
Photon
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?

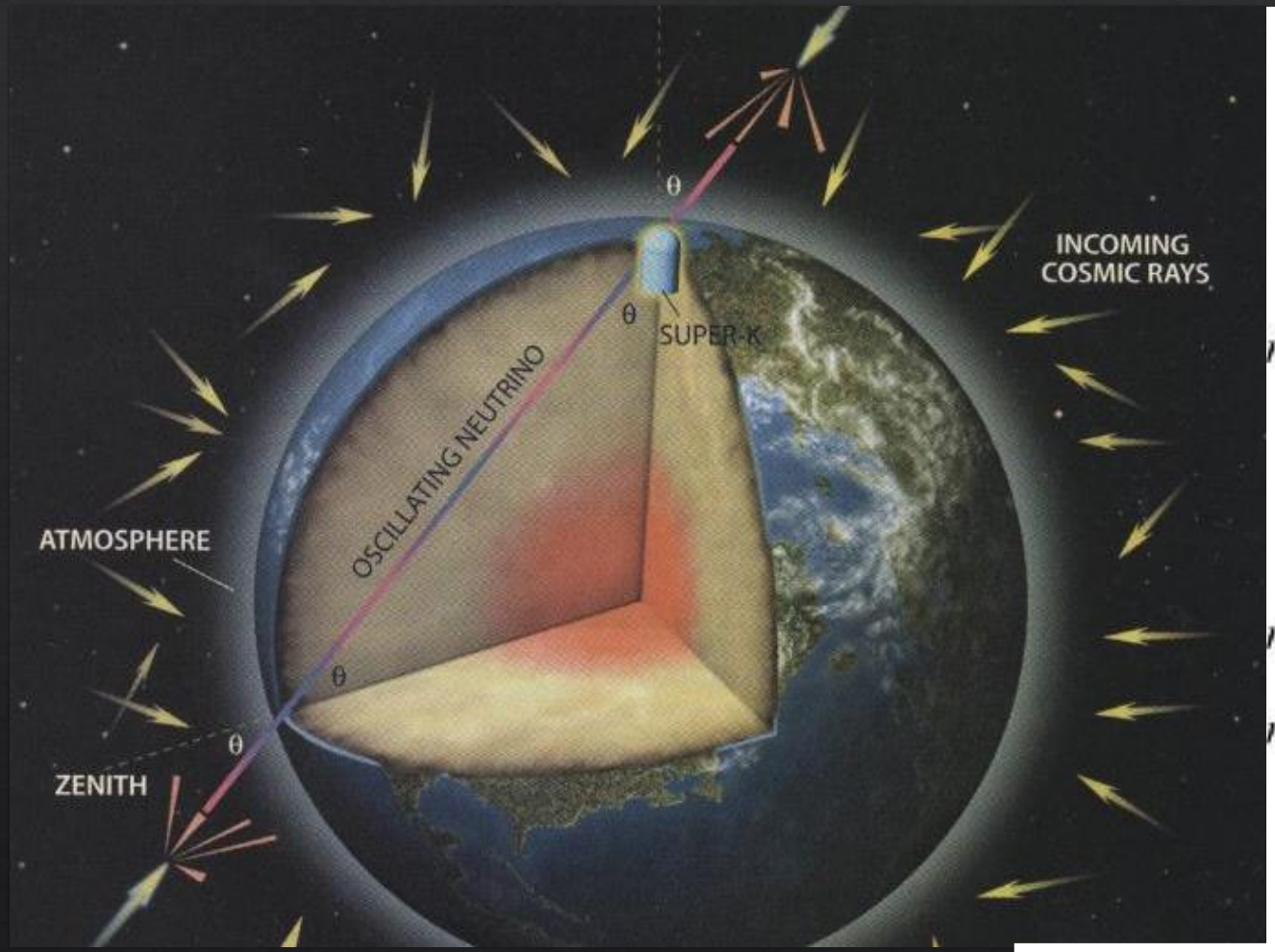
- **Particle Physics**
- **Particle Detectors**

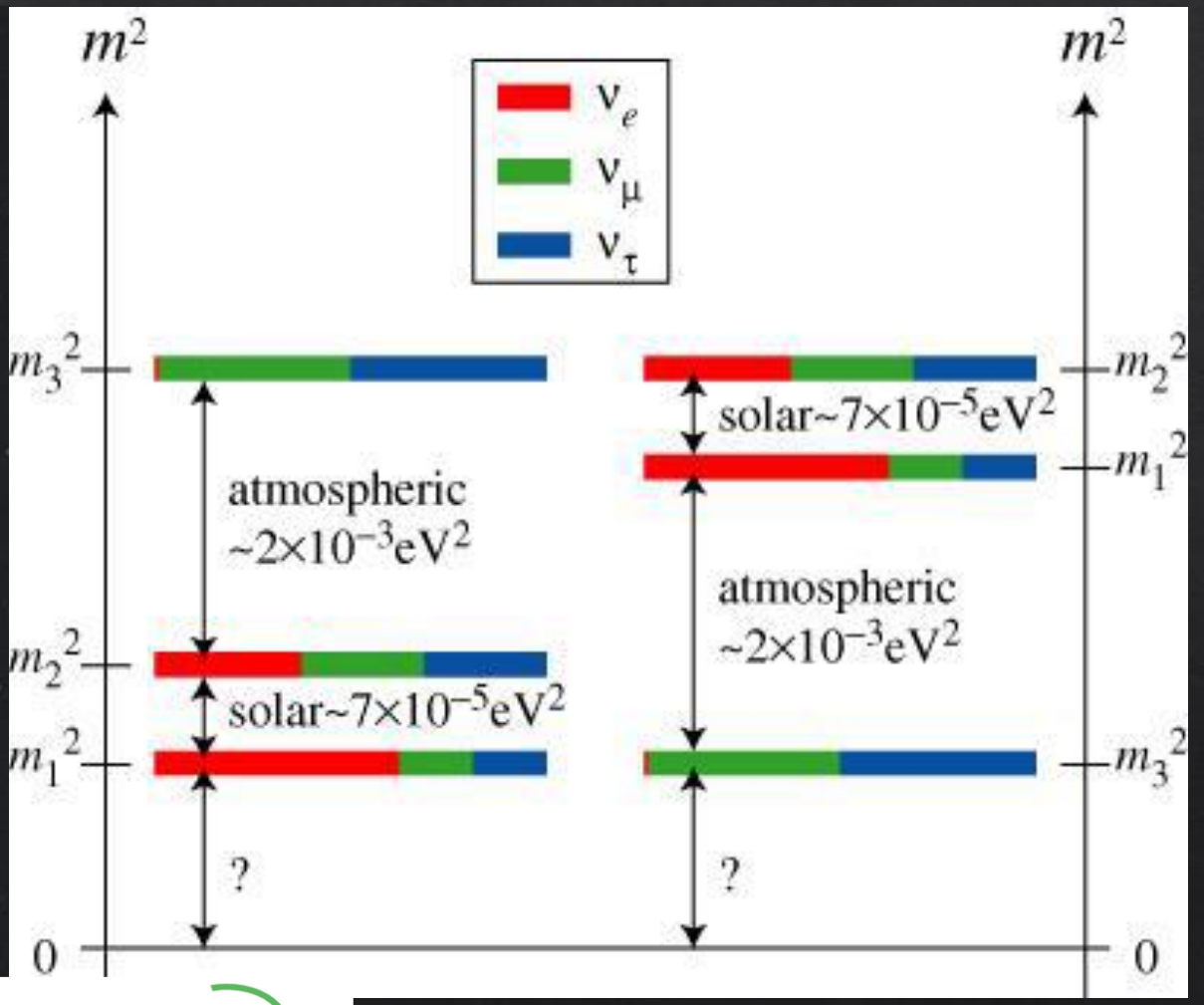
- Din ce este constituită materia?
- Din ce este compus universul?
- Care este originea universului și cum a evoluat?
- De ce se comportă așa universul?
- Cum va evolua?
- ....

Modelul Standard –
răspunsul la toate întrebările?

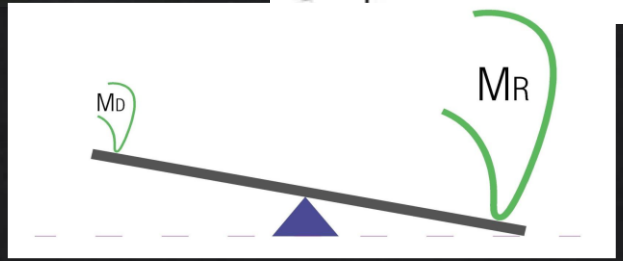
**NU!**

# Cum acomodăm în teorie masa neutrinilor?

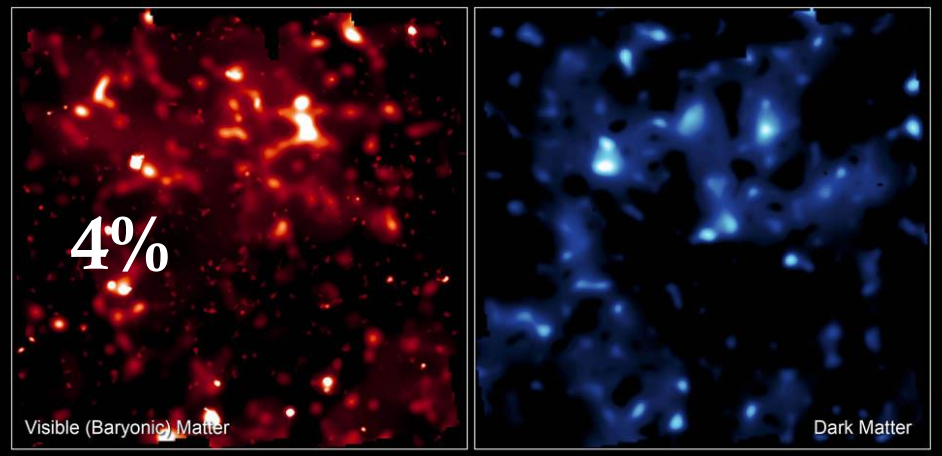


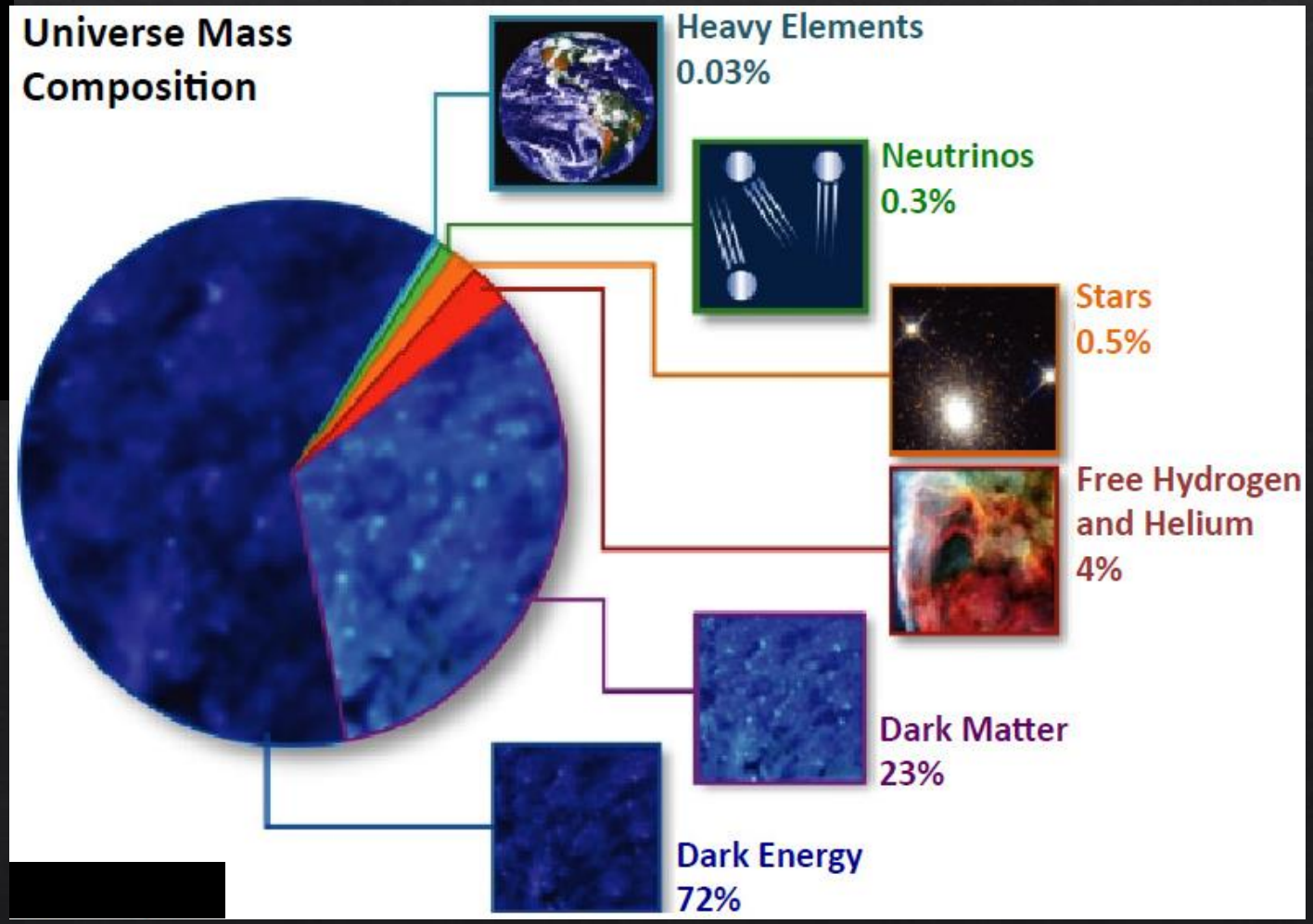




matricea de mixing a neutrinilor?



# Ce este ,,dark matter”?

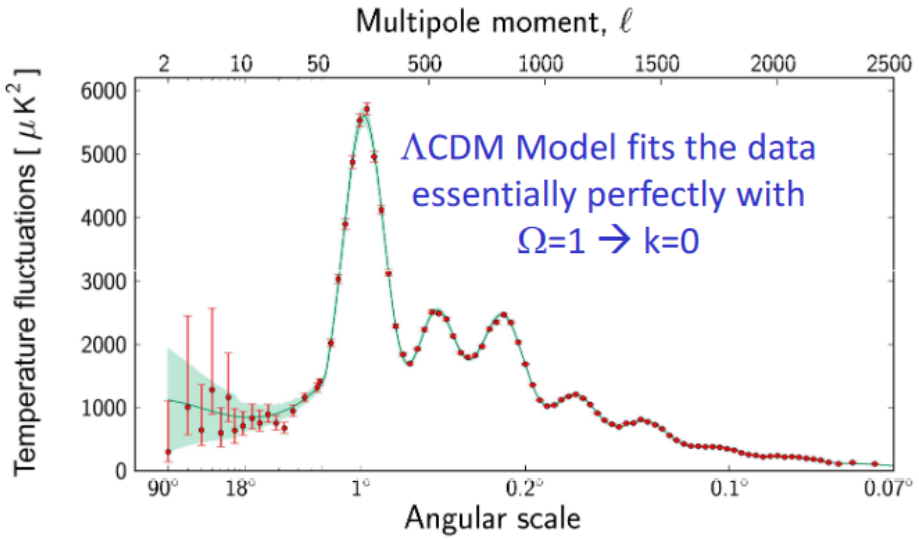


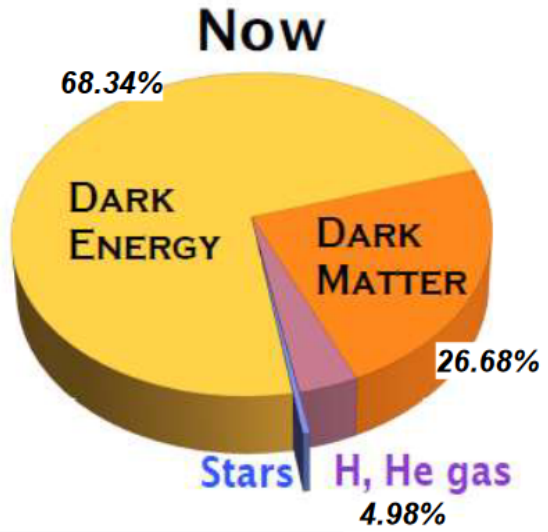



# Urmează: **Pascal Pralavorio's on Dark matter**

## 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

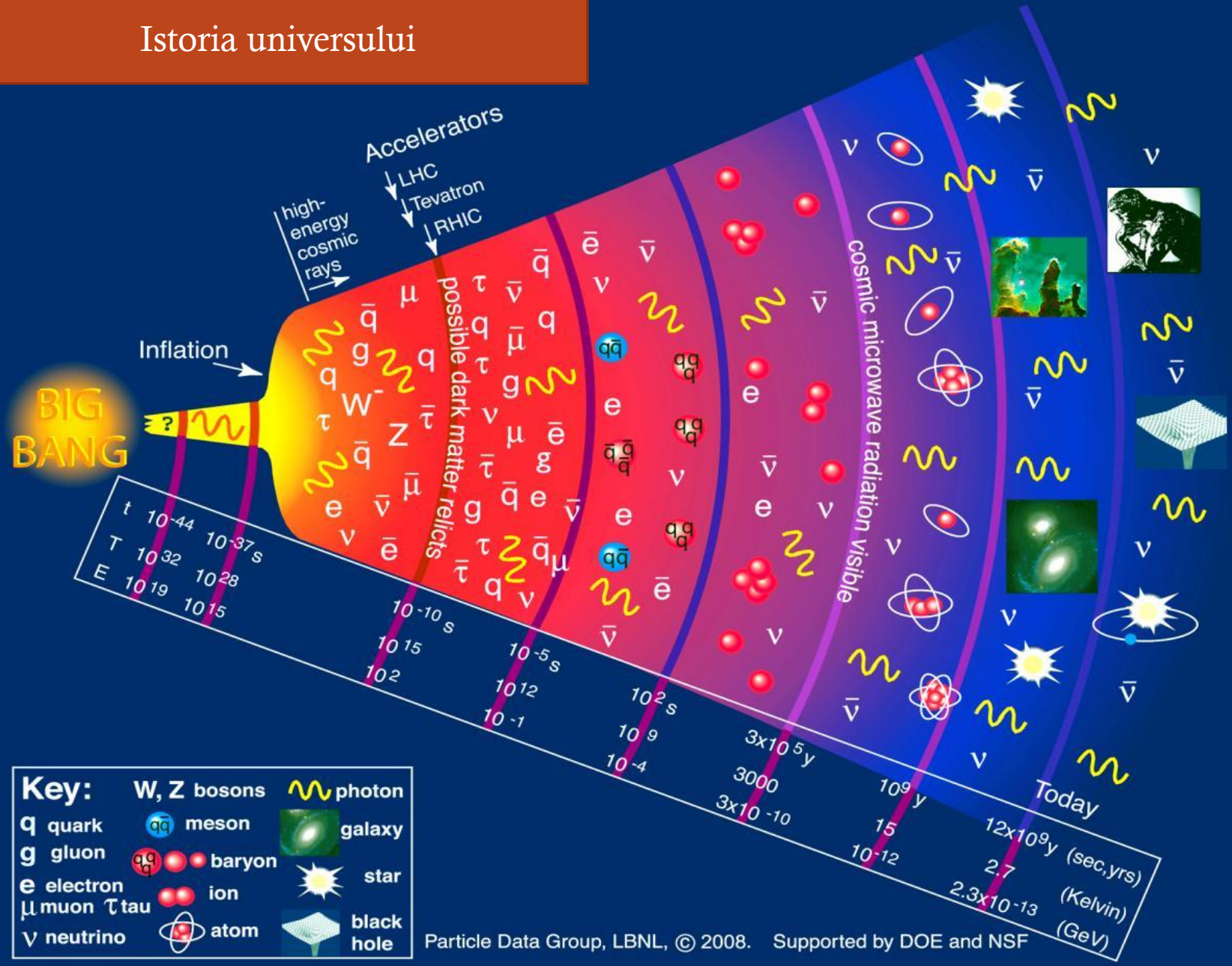
$B^0$

CP

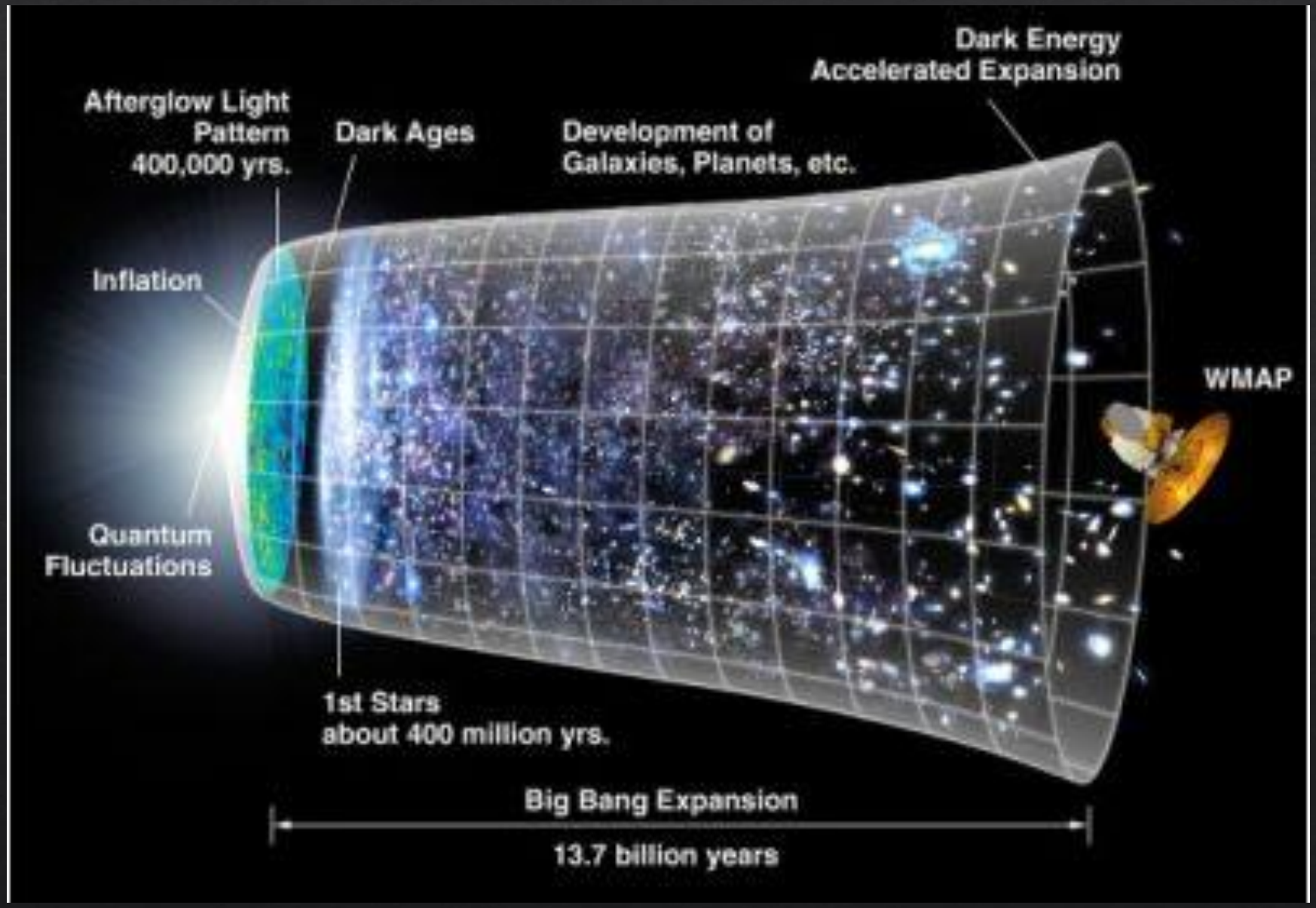
anti-beauty

$\overline{B^0}$

# 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

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4. **Cum detectăm particule elementare?**

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