Introduction to Particle Physics

Swedish Teachers program 2016

Lecture I

The fundamental components of matter and interactions

Disclaimers

- Only a simplified description of the fundamental components is given;
- Basic presentation of the SM mathematical framework by introducing elements of Analytical mechanics, Quantum FieldTheory, Special Relativity and Quantum Mechanics;
- There are enough reasons the attempt may fail!...nevertheless let's try!

Lecture I

- Fundamental constituents of matter;
- Description of the three fundamental interactions;
- Analytical mechanics as introduction to the Standard Model

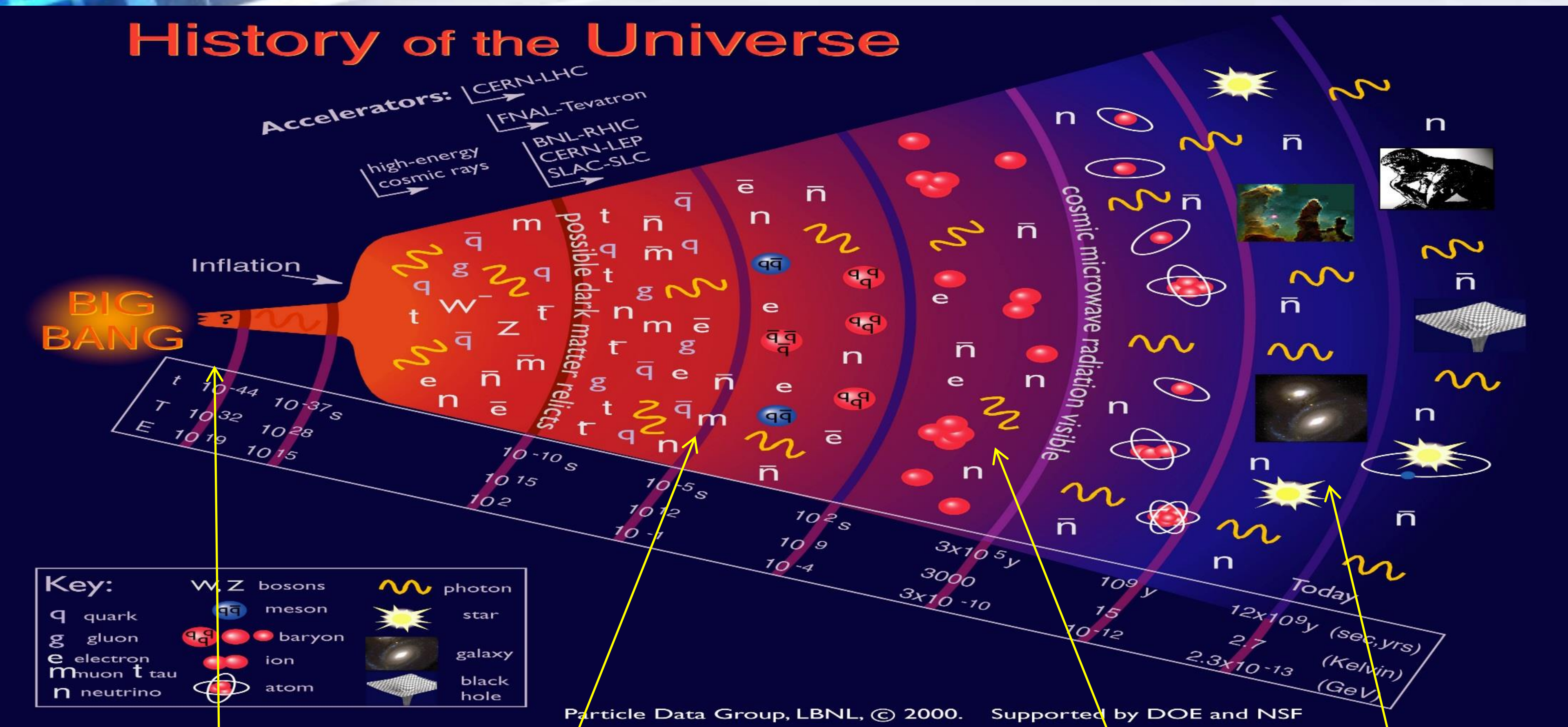
Hubble Ultra Deep Field

Particle physics

The questions addressed by the particle physics are the same that guided the development of Natural Philosophy in the course of History:

- How does the Universe work?
- Where does it come from?
- Where is it going?
- What are the ultimate components of matter?
- How do they "move" ?
- What "moves them"?

Particle Physics in context



Cosmology

Quark/gluon plasma

Nuclear physics

Astrophysics

Fundamental constituents

- Matter constituents: Pointlike, massive particles (also named mass field):
  - Quarks and leptons (fermions, spin 1/2)*);
- Vector fields: particles acting as force carriers:
  - Photon, $W^{\pm}$,Z^{o} , gluons (bosons , spin 1) *);
- Scalar field: Burt-Englert-Higgs-field filling the Universe and providing mass to fundamental particles;
  - BEH boson.

*) see next slide

Spin, bosons and fermions

- bosons and fermions have different value of the “intrinsic angular momentum: spin” (like a spinning top);
- Bosons spin=nħ ; fermion’s spin= 1/2nħ [n=1,…];

- ħ is the minimum quanta of action the quantum system can exchange. Dimensionally it is energy*time or angular momentum. ħ= $6.63\ 10^{-34}$ Joule*s;

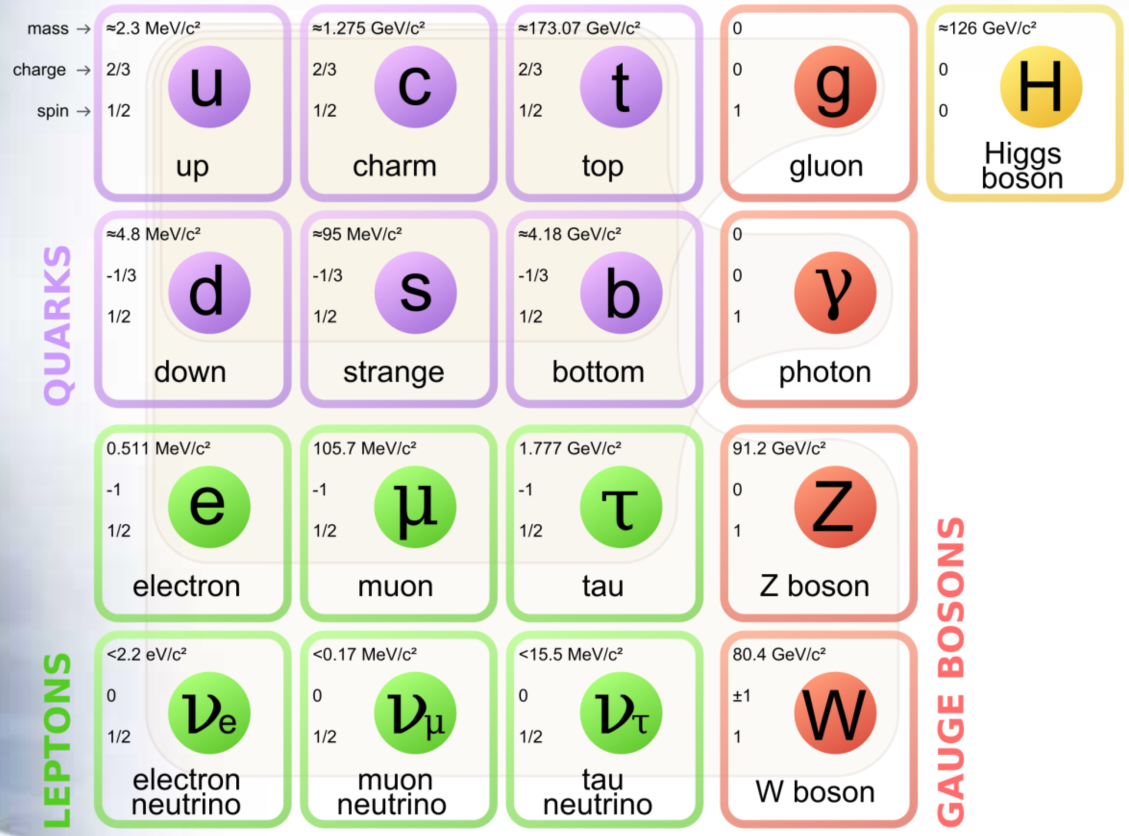
- bosons obey to Bose-Einstein statistics and fermions obey to Fermi-Dirac statistics when they have to distribute in different energy levels for reaching an equilibrium configuration.

Fundamental Interactions

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

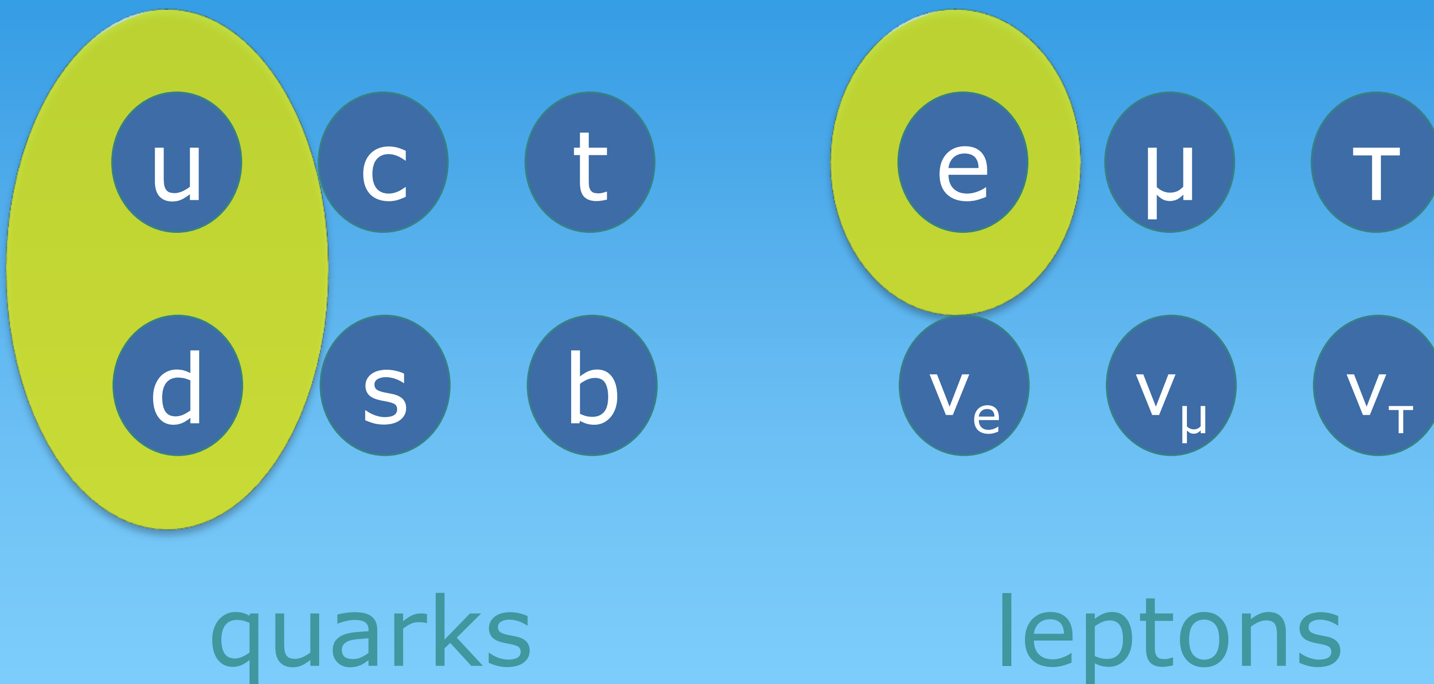
At one glance



A bit of history

u	c	t	e	μ	τ
d	s	b	ν_e	ν_μ	ν_τ

quarks leptons

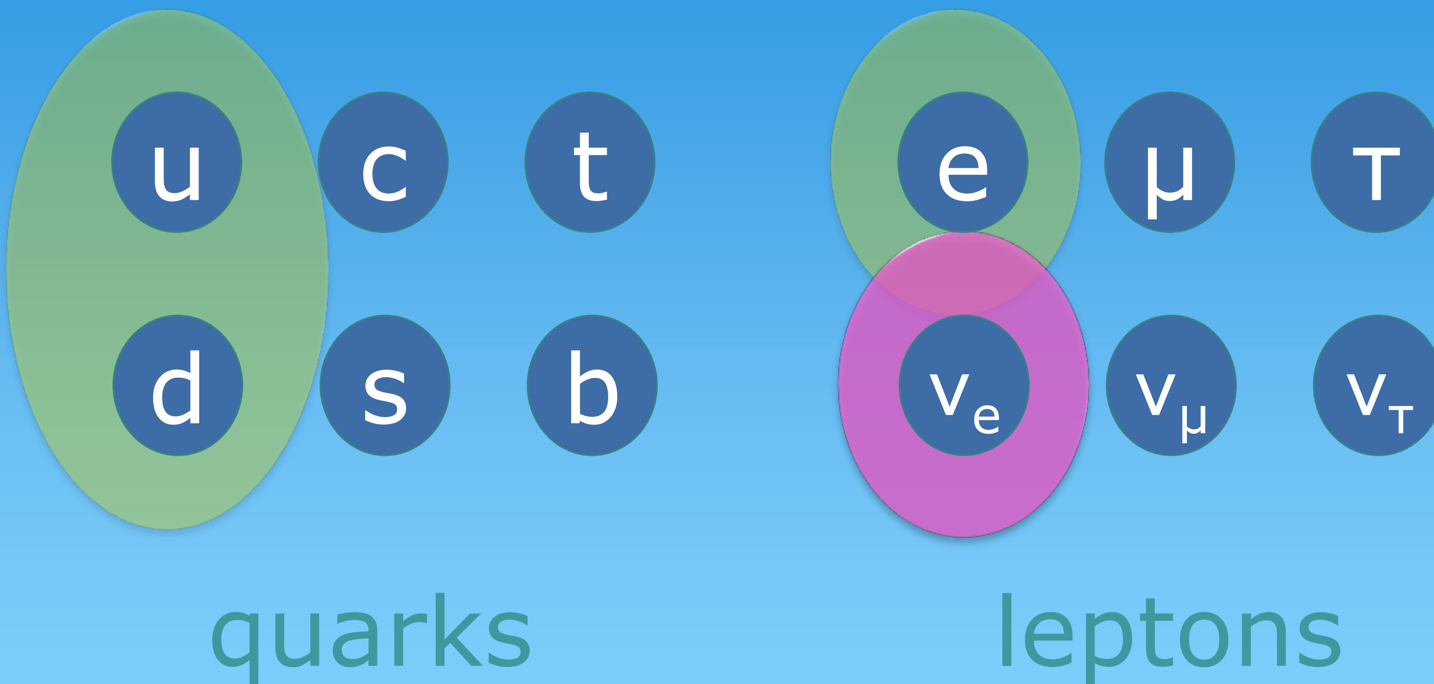


u,d proposed 1960s, discovered ~1968

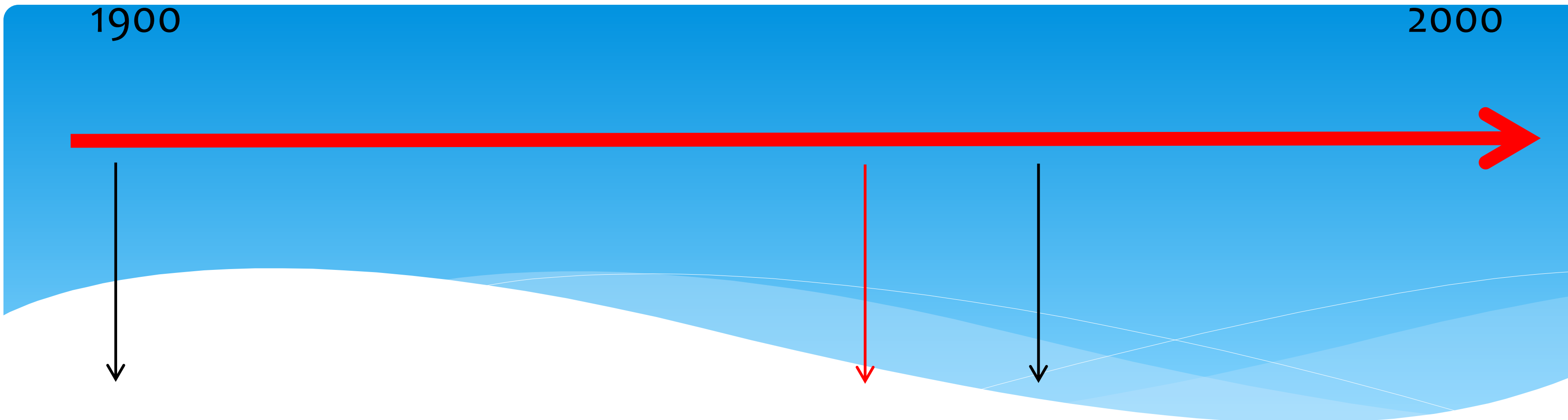
e discovered 1897

1897
Electron
J.J. Thomson,
Philosophical magazine **44**:293

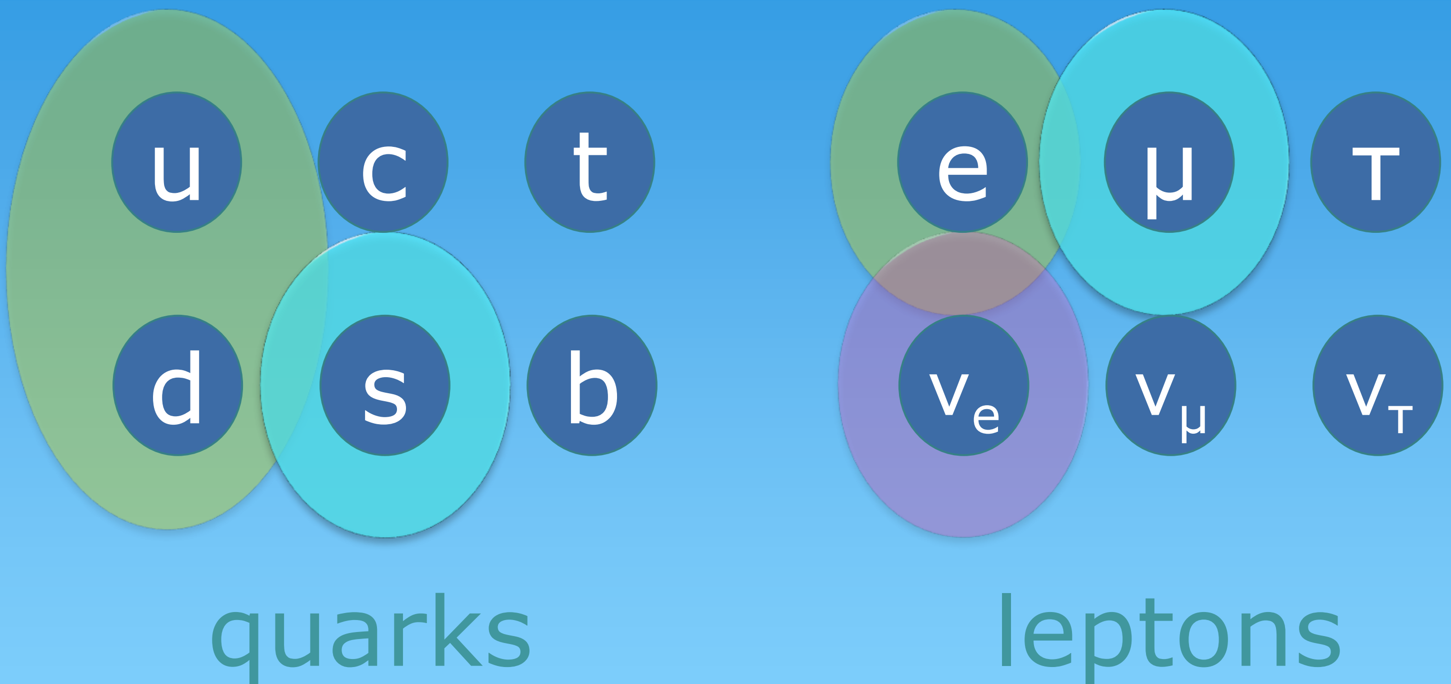
1969
up, down, strange quarks
E.D. Bloom *et al. Physical Review Letters* **23** (16): 930
J. M. Breidenbach *et al. Physical Review Letters* **23** (16): 235



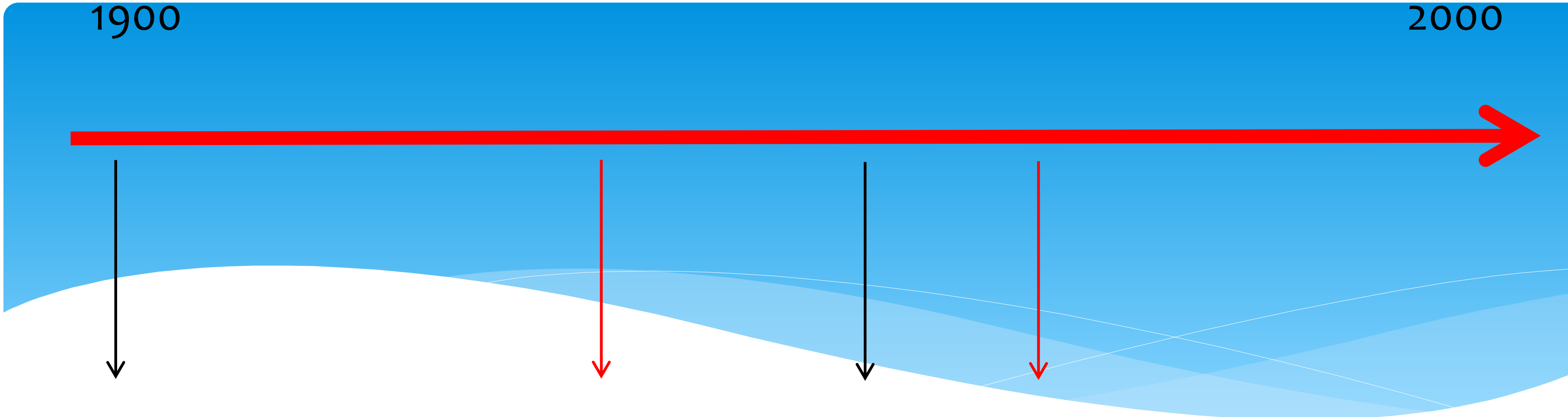
Radioactive decay (inferred 1930s, seen 1956)



1956
Electron neutrino
F. Reines, C.L. Cowan, *Nature* **178** (4531): 446

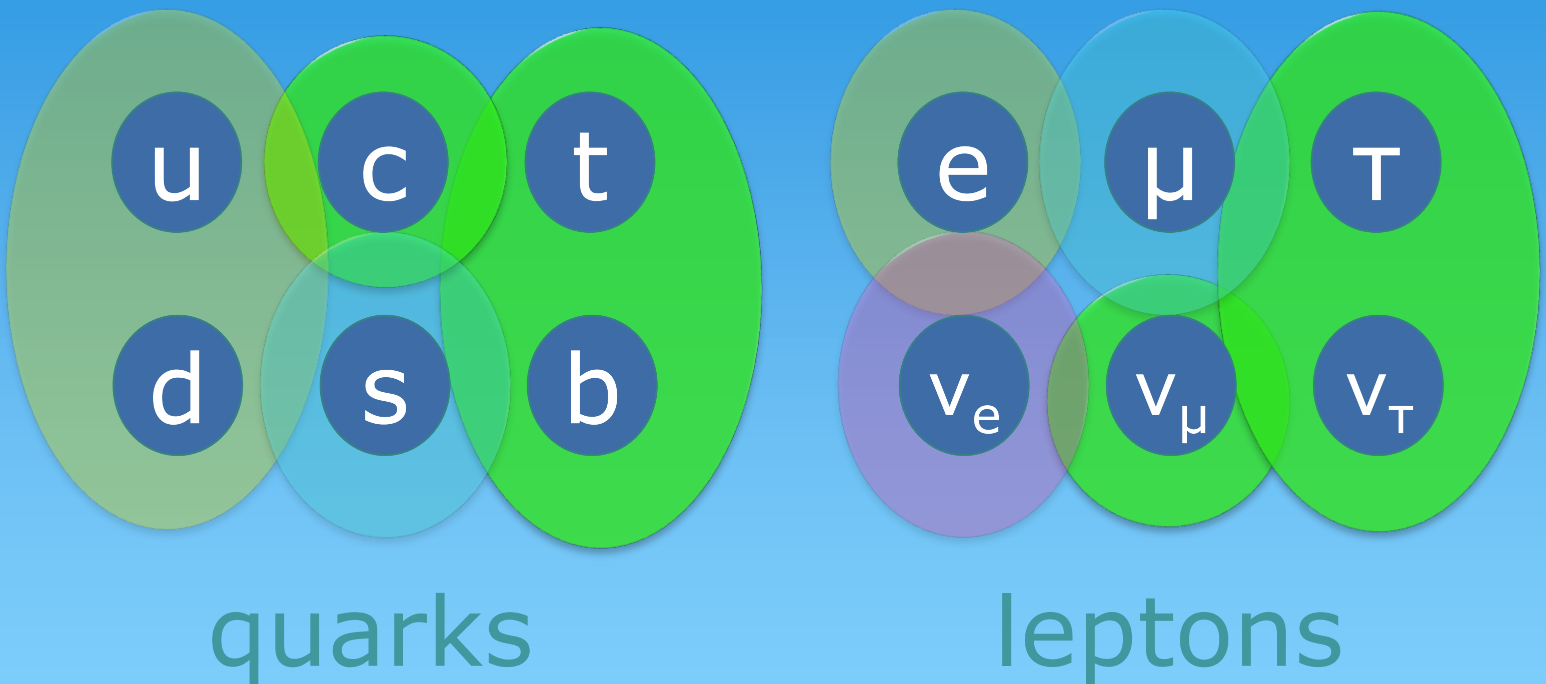


Cosmic ray experiments (1930s, 1940s)

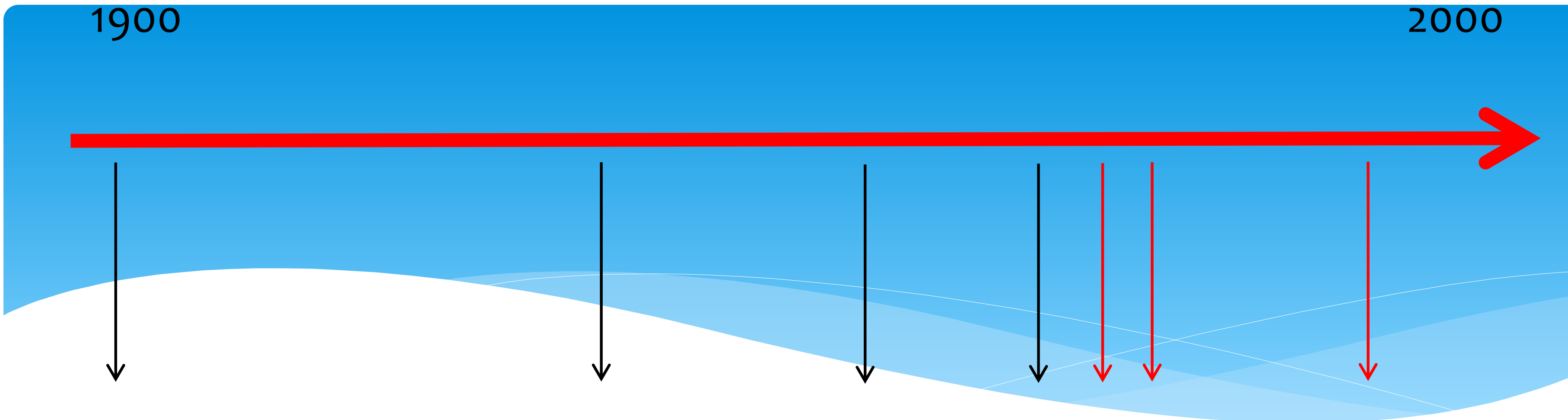


1937
Muon
S.H. Neddermeyer, C.D. Anderson, *Physical Review* **51** (10): 884

1969
up, down, strange quarks
E.D. Bloom *et al. Physical Review Letters* **23** (16): 930
J. M. Breidenbach *et al. Physical Review Letters* **23** (16): 235



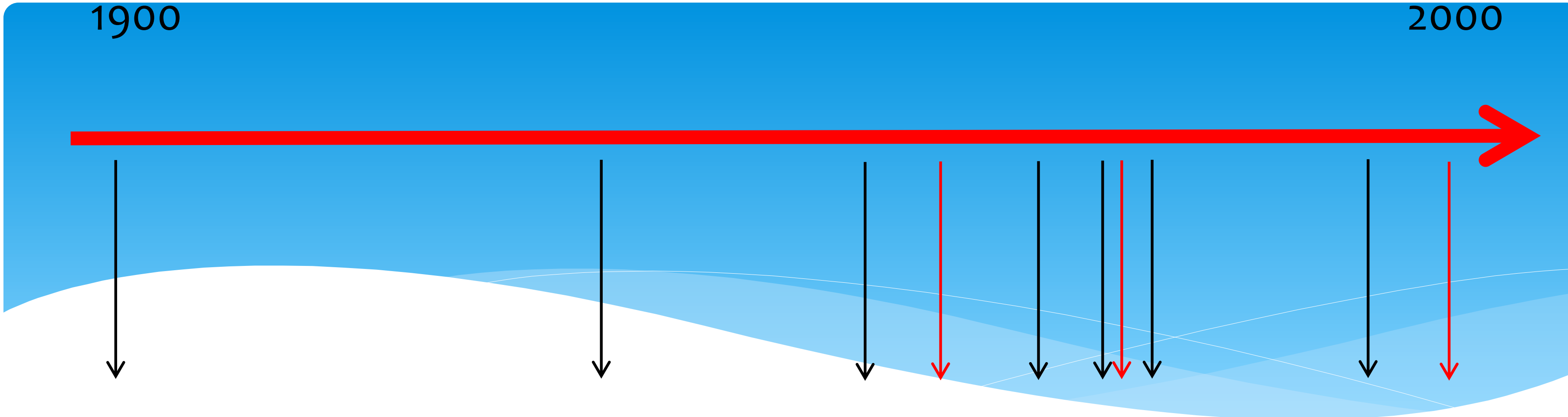
Collider experiments (1960s -)



1974
Charm quarks
J.J. Aubert *et al.* *Physical Review Letters* **33** (23): 1404
J.-E. Augustin *et al.* *Physical Review Letters* **33** (23): 1406

1977
Bottom quarks
S.W. Herb *et al.* *Physical Review Letters* **39** (5): 252.

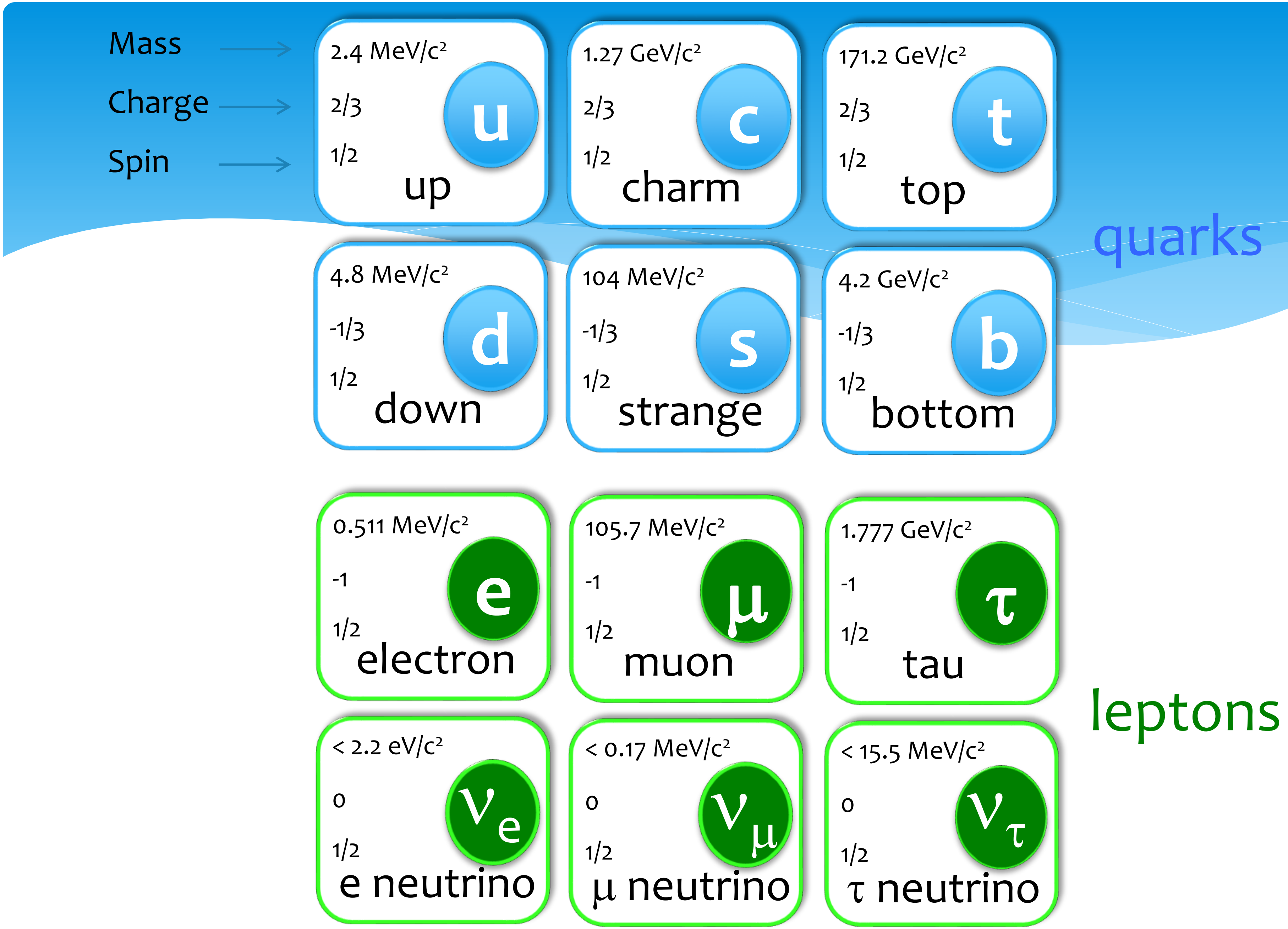
1995
Top quarks
F. Abe *et al.* (CDF collaboration) *Physical Review Letters* **74** (14): 2626–2631.
S. Arabuchi *et al.* (D0 collaboration) *Physical Review Letters* **74** (14): 2632–2637.



1962
Muon neutrino
G. Danby *et al. Physical Review Letters* **9** (1):36

1975
Tau lepton
M.L. Perl *et al. Physical Review Letters* **35** (22): 1489.

2000
Tau neutrino
K. Kodama *et al.* (DONUT Collaboration),
Physics Letters B **504** (3): 218.


Mass
Charge
Spin
2.4 MeV/c²
2/3
1/2
u
up
1.27 GeV/c²
2/3
1/2
c
charm
171.2 GeV/c²
2/3
1/2
t
top
quarks
4.8 MeV/c²
-1/3
1/2
d
down
104 MeV/c²
-1/3
1/2
s
strange
4.2 GeV/c²
-1/3
1/2
b
bottom
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
leptons
< 2.2 eV/c²
0
1/2
νe
e neutrino
< 0.17 MeV/c²
0
1/2
νμ
μ neutrino
< 15.5 MeV/c²
0
1/2
ντ
τ neutrino

And … antimatter

Einstein's equation of motion*: $E^2 = p^2c^2 + m^2c^4$

Two energy solutions for the same mass;

- Matter
- Antimatter

Every fermion has an antimatter version.

Same mass, opposite charge

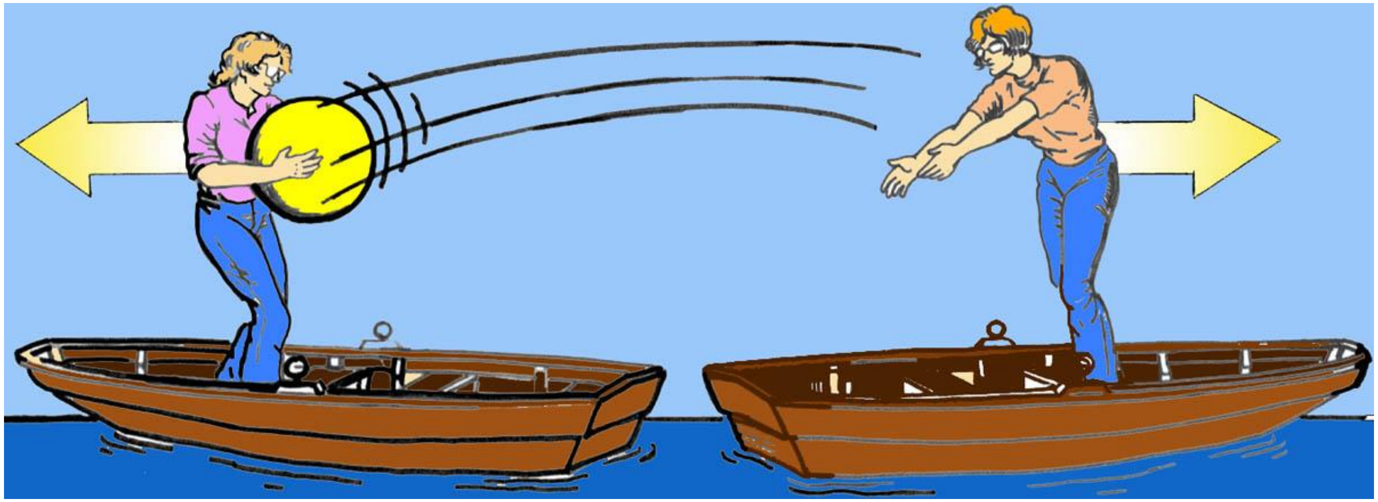
eg. antiquark $\bar{q}$, antimuon μ^+, antineutrino $\bar{\nu}$

*(and others, more famously Dirac)

Metaphors of the Fundamental interactions:

Matter is held together by forces;

- mediated by force carrying particles (bosons; spin 1)



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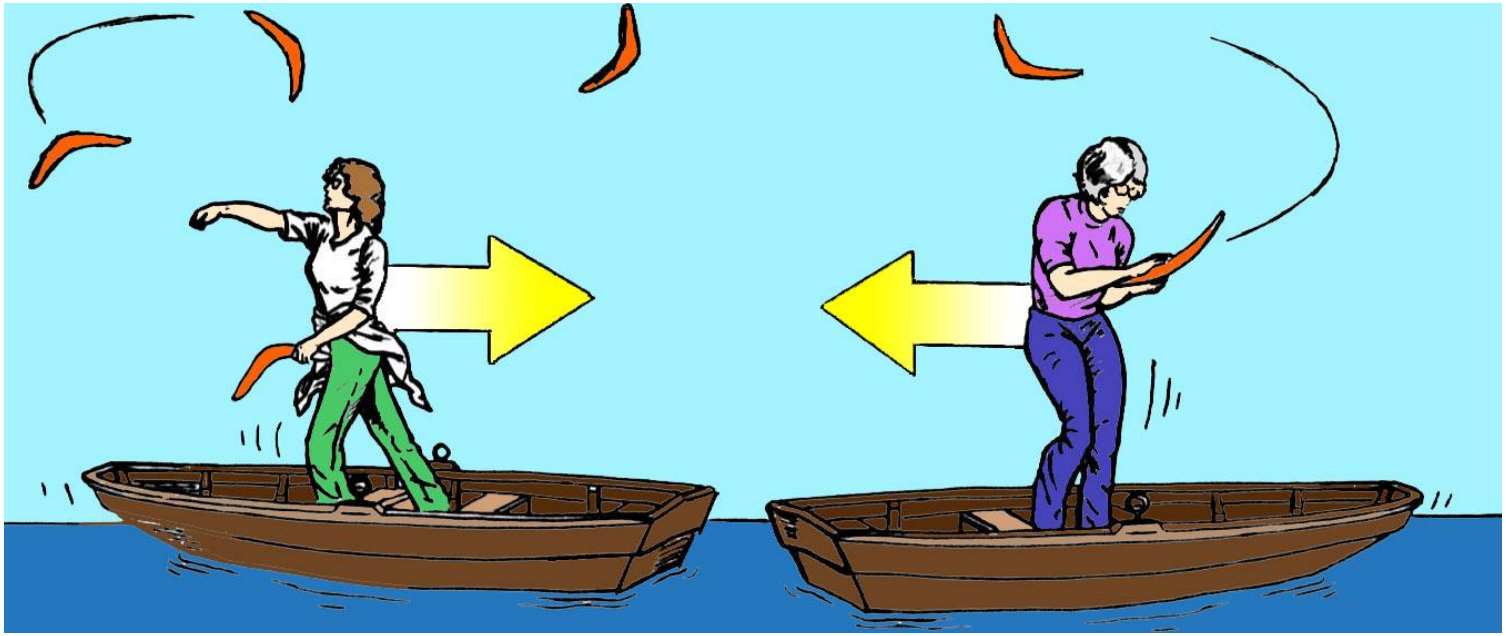


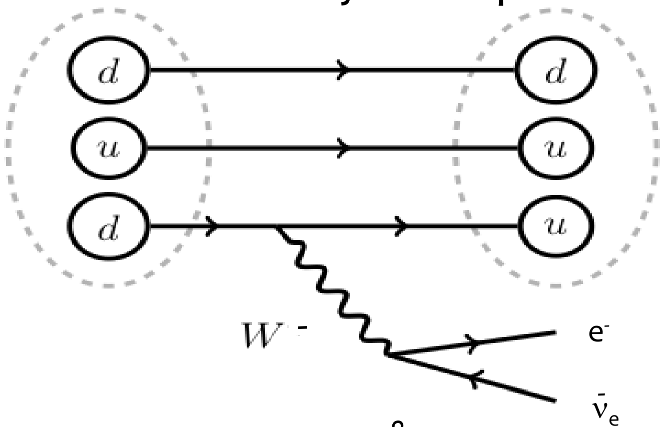
Weak force interactions: Feynman diagrams

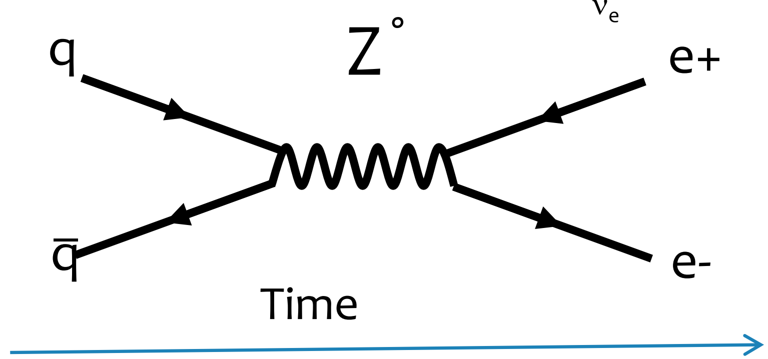
The diagrams are useful to calculate the interaction probability in one vertex

W couples to:
Upper and lower members of a fermion generation.

Z couples to:
Matter and antimatter versions of a fermion.

neutron decay into a proton

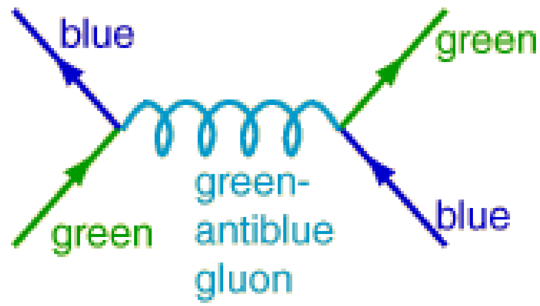




Strong and EM interactions: Feynman diagrams

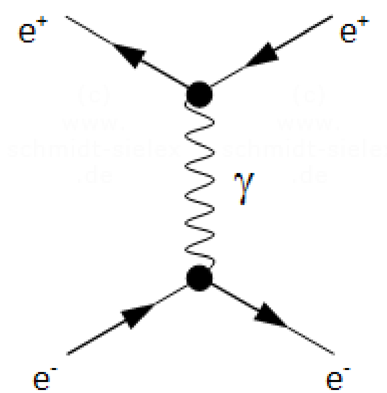
Strong interaction

Time



Gluon-mediated interaction between two quarks.

Electromagnetic interaction



Time

What the standard Model is?

- Since the 1970s, particle physicists have described the fundamental structure of matter using an elegant series of equations called the Standard Model (SM);

- Three fundamental interactions and the HB field are described but the gravitation;

SM ingredients

- SM is based on the Quantum Field Theory (QFT) and integrates:
  - Concept of the Analytical Mechanics (Classical mechanics);
  - The Special Relativity (physics revolution);
  - The Quantum Mechanics (physics revolution)
  - tensor calculation, group theory, (mathematical tools).
- Rather complex mathematical framework

Analytical Mechanics

(XVIII-XIX century: leibnizMaupertuis, D'Alambert, Poisson, Eulero,Jacobi,Hamilton, Lagrange,...);

- Re-formulation of the Newtonian mechanics in a generic coordinate system, to deduce the equation of motion x(t) of a body, provided the Lagrangian of the body is known (L=T-V);

How do we find $x(t)$?

$x(t)$ minimizes something

- This is an axiom
- The thing that $x(t)$ minimized is called “the action” and is denoted by S
- There is one action for the whole system
- Similar to a minimum of a function

$$\min[f(x)] \Rightarrow x_0, \qquad \min[S(x(t))] \Rightarrow x_0(t),$$

- The condition for a minimum of a function is $df(x)/dx = 0$. What is the equivalent one for a minimum of an action?

What is S?

$$S = \int_{t_1}^{t_2} L(x, \dot{x}) dt, \qquad \dot{x} \equiv \frac{dx}{dt} = v$$

- The solution of the requirement that S is minimal is given by the E-L equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = \frac{\partial L}{\partial x}$$

- Once we know L we can find $x(t)$ up to initial conditions
- To find a minimum of function we solve an algebraic eq. For the action we have a differential eq.
- Mechanics is reduced to the question "what is L?"

Y. Grossman HEP theory (1) CERN, July 1, 2015 p. 6

An example: Newtonian mechanics

We assume particle with one DOF and

$$L = \frac{mv^2}{2} - V(x)$$

- We use the E-L equation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{x}}\right) = \frac{\partial L}{\partial x} \qquad L = \frac{mv^2}{2} - V(x)$$

- The solution is $-V'(x) = m\dot{v}$, aka $F = ma$
- Here $F = ma$ is the output, not the starting point!
- So how do we find what is L?

How do we find L?

- To ensure the invariance of the Mechanics formulas (covariance) under coordinates transform, symmetries have to be provided to L;
- Asking L is invariant under (e.g.):
- coord. Transf. in 1d x ->-x ;
- Rotations in 3d;

Summary Lecture I

- quarks and leptons (fermions, spin=1/2h) to account for the visible mass in the Universe;
- force carriers (bosons, spin=1h) for the three fundamental interactions;
- The analytical mechanics: known the Lagrangian L=T-V, by the Euler-Lagrange equation, the equation of the motion x(t) can be found. We will see that this procedure will 'inspire' the QFT.