Introduction to Particle Physics

Swedish Teachers program 2017

Program

Lecture I

Program

- Lecture I
  - Exploring the particle physics world
- Lecture II
  - Introduction to the Standard Model (SM)
- Lecture III
  - Beyond the SM

Lecture I
Exploring the particle physics world

- Introduction
- Foundations of Quantum Physics;
- Fundamental particles and interactions

Introduction

- Particle Physics is the study of :
  - the fundamental constituents of the matter;
  - and the forces acting among them;
- Purpose
  - provide some help for a unified view of the Universe
- Disclaimer
  - The discussion level of the subject will be mostly qualitative and descriptive, suitable for an introductory course!

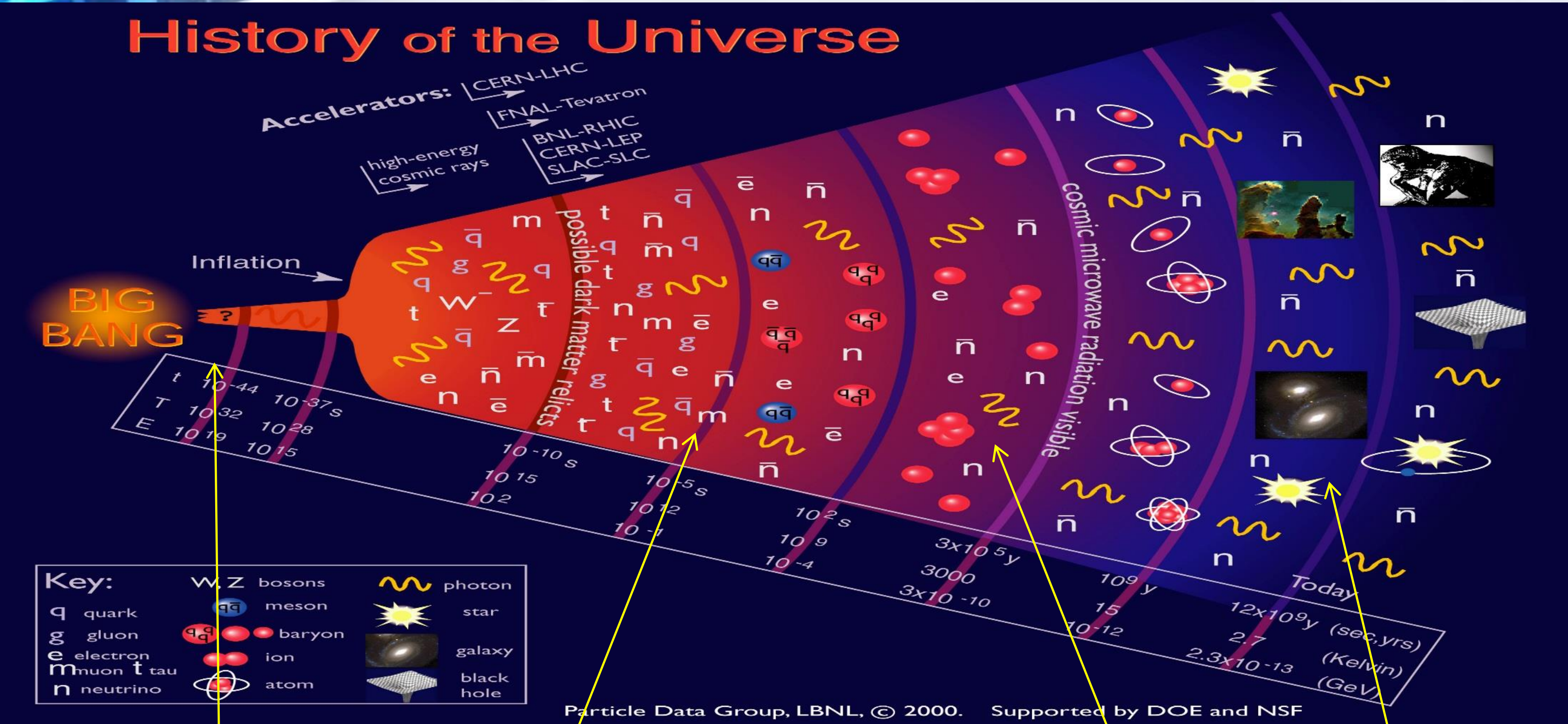
Hubble Ultra Deep Field

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

Foundation of quantum physics

What a fundamental particle is?

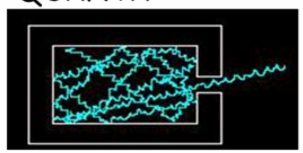
- Our sensory experience would lead us to say it has a defined shape and size and therefore localized in the space, something like spheres, with radius, mass and charge;
- Experiments have shown that our extrapolated sensory picture of the basic constituents of the matter is erroneous!!

Foundations of Quantum Physics

Credit to R. Landua

M. Planck

1900: ELECTROMAGNETIC RADIATION IS EMITTED IN QUANTA

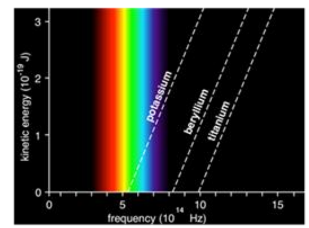


$$\varepsilon = h\nu \qquad I(\nu) \sim \nu^2 \frac{h\nu}{e^{\frac{h\nu}{kT}} - 1}$$

P. von Lenard

1902: PHOTOELECTRIC EFFECT

"The electron energy doesn't show the slightest dependence on the light intensity"



A. Einstein

1905: LIGHT IS EMITTED AND ABSORBED IN QUANTA

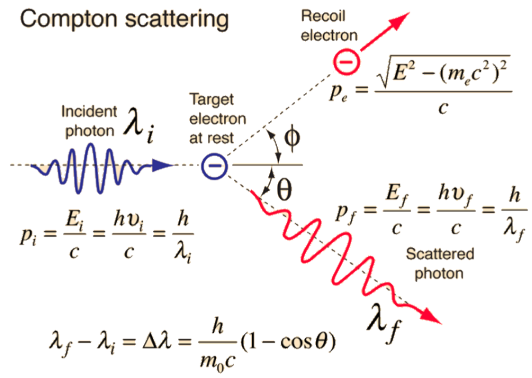
$$E_{max} = h\nu - W$$

"My only revolutionary contribution to physics"

Planck constant h =6.63 10^{-34} J*s

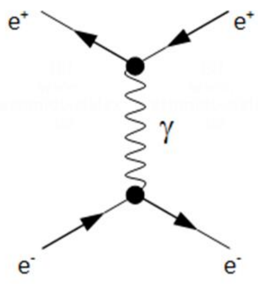
Foundations of Quantum Physics

- 1920- Scattering of radiation with free electrons (Compton effect):
  - The e.m. wave play a role of the particle of rest mass zero, the photon p=E/c ($E^2=m_0^2c^4+p^2c^2$),
  - Applying the E and p conservation laws and assuming E=hv we get the Compton formula where h has the same numerical value as in the ph.e. effect and in the blackbody rad.!



The E.m. wave has a corpuscular behavior!

  - Energy and momentum exchanged between e.m. radiation and charge particle are those corresponding to a photon. Completely new principle in the Physics!
  - The concept of photon suggest a simple pictorial representation



Foundations of Quantum Physics

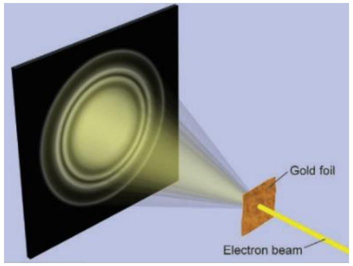
L. de Broglie

1924- Particle and Field (L. de Broglie)

And if we assume that a particle of energy and momentum E and p has an associated **matter field** with frequency **ν=h/E and wavelength λ=h/p?**

1927- Diffraction of electrons trough crystal poudre (Germer, Thomson..)

Indeed electrons diffract in crystals as Xray do!
Massive particles behaves as matter waves (diffraction, interference..)!



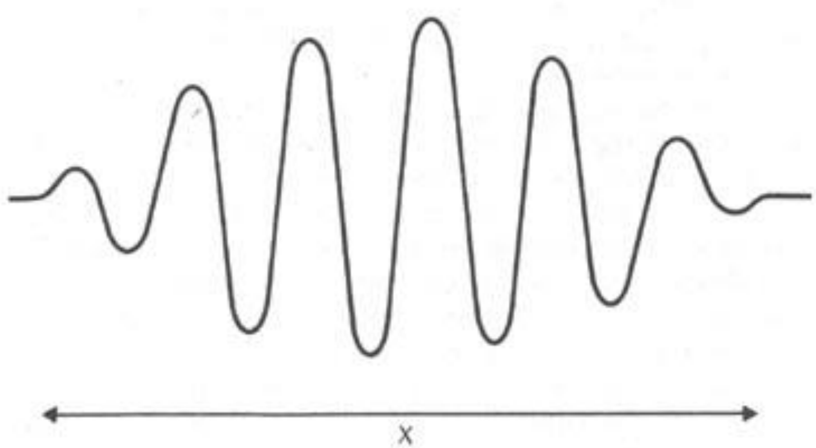
Particles behaves as wave!

So particle (E,p) and wave (ν,λ) variables are linked via h.
Particle-wave Duality!

$$E=h\nu \text{ and } p=h/\lambda=\hbar K$$

Foundations of Quantum Physics

- A particle localized in a certain region of space (Δx) is associated with a wave packet whose amplitude is important only in that region;
- The packet extending over Δx requires the values of wave numbers K have an appreciable amplitude within a range Δk such that according to the theory of Fourier analysis $\Delta x \Delta k \approx 2\pi$



a wave packet corresponding to a particle located somewhere in the region X

Heisenberg’s uncertainty principle

Different wavelengths implies several values of p such $\Delta p = \hbar \Delta k$.
Then $\Delta x \Delta k \approx 2\pi$ becomes $\Delta x \Delta p \approx h$

- Since the incertitude on the position and particle momentum are known with less accuracy then the most general relation is

$$\Delta x \Delta p \geq h$$

Heisenberg's uncertainty principle

- *It is impossible to know simultaneously and with exactness both the position and the momentum of a particle.*

This principle is a fundamental fact of the nature!

- The relation $\Delta E \Delta t \geq h$ also helds.

Again, what a fundamental particle is?

- An object with corpuscular-wave behavior (duality);
- The Heisenberg's incertitude principle and the minimum quanta of action h impose the Quantum Mechanics for the description of the particle dynamic state.
- Classical mechanics becomes inadequate!

Fundamental particles and interactions

Fundamental Components of the matter: quarks and leptons

- To put some order in the particle zoo (hundreds of particles observed) the quark model was proposed and developed during 1960s (…and accepted in 1970s!);

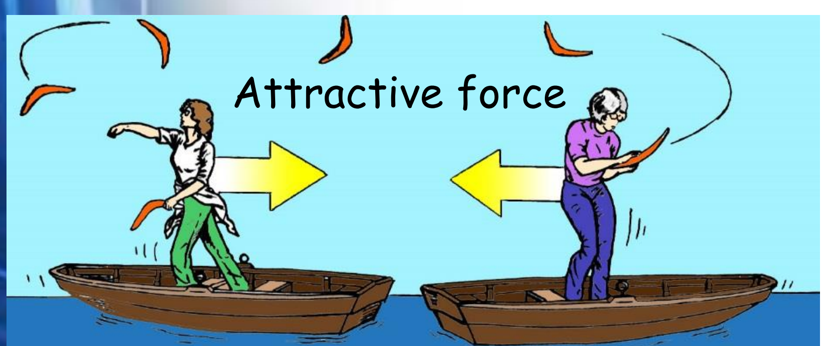
- Particles as neutrons and protons are described by a combination of a reduced number of fundamental constituents: **quarks;**

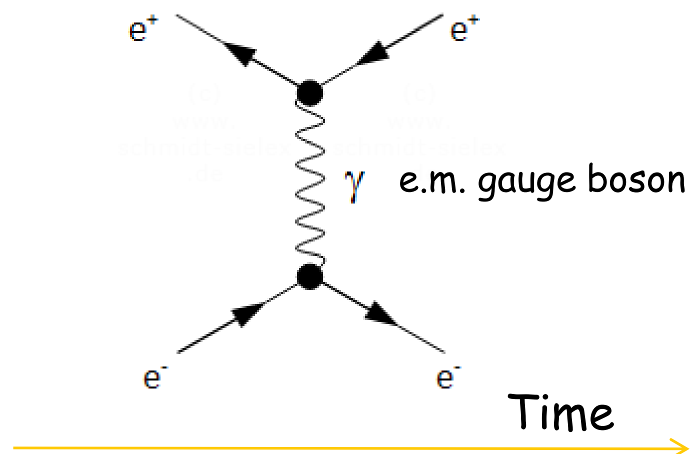
- **leptons** (electron, neutrinos..), with the quarks are the fundamental components of the ordinary matter we are made of.

Fundamental interactions

Interactions between particles are described by the exchange of force mediator known as **gauge bosons**.

Below metaphors of repulsive and attractive forces.





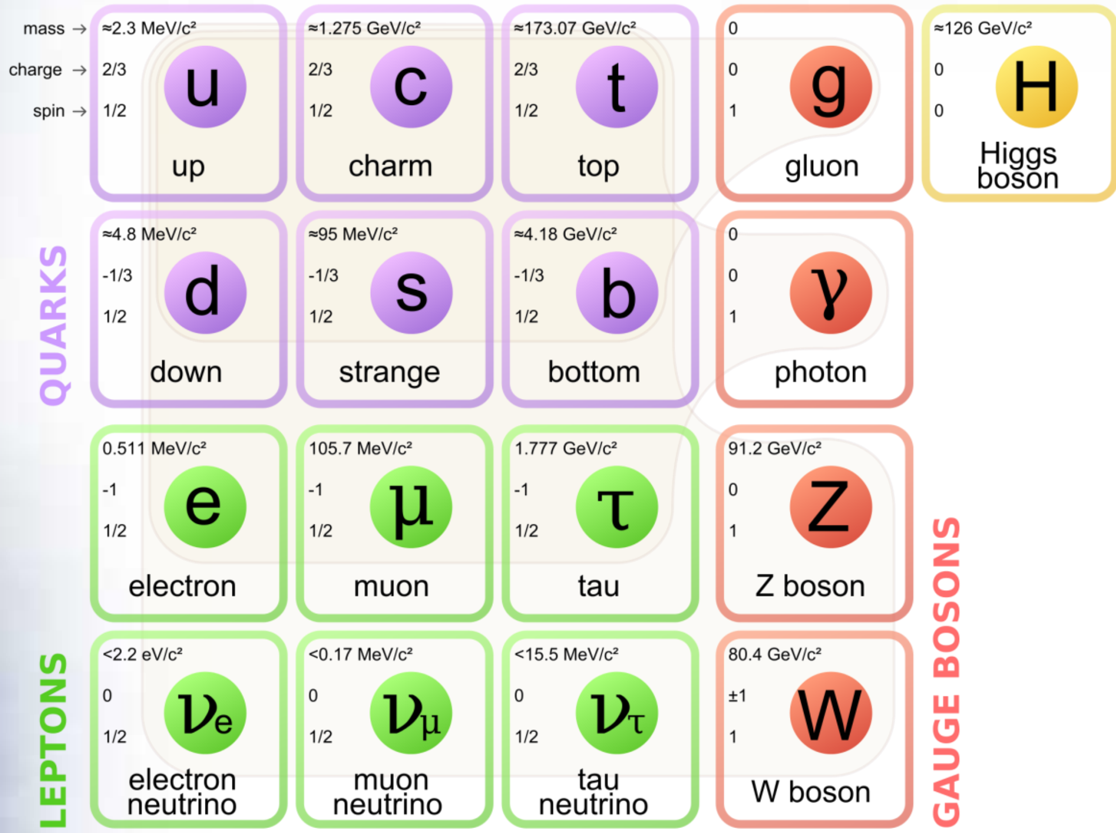
Electromagnetic interaction

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



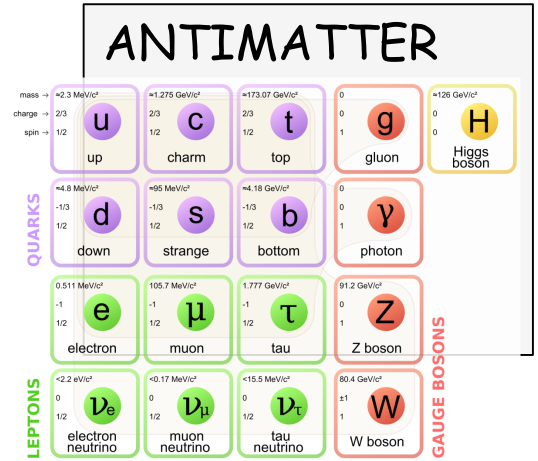
And … antimatter ?

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

Two energy solutions for the same mass;

- Matter
- Antimatter

Every fermion has an antimatter version.
Same mass, opposite charge
eg. Anti-quark q, anti-muon μ^+, anti-neutrino ν



Summary on Quarks, leptons, bosons

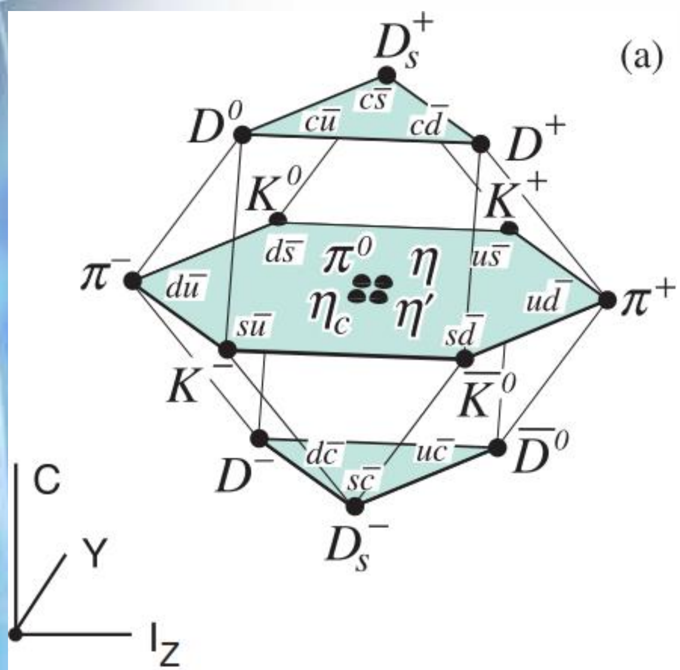
- **Matter constituents:**
  - **quarks and leptons**, point-like massive particles (also named mass field), **fermions** with spin=$\frac{1}{2}\hbar$;

- **Particles mediating the interactions:**
  - the **gauge bosons** with spin=1ħ as photon, $W^{\pm}$,Z° and gluons,

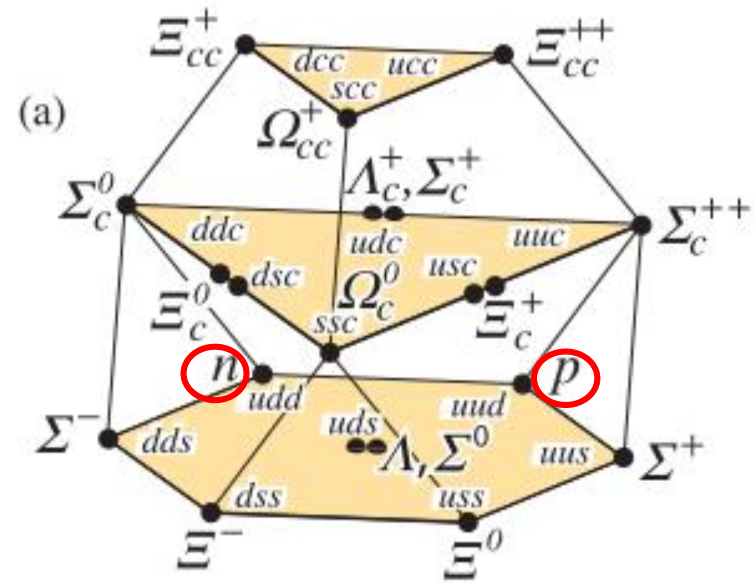
- **Burt-Englert-Higgs-field providing mass to fundamental particles**;
  - BEH field fills the Universe. The observed boson with spin=0 confirmed his existence!

*) $\hbar = h/2\pi$ quantum unit of angular momentum =1.05 10^{-34} J*s

Some Mesons and Baryons quark content



Multiplets of mesons ($q\bar{q}$) made of u,d, s and c quarks



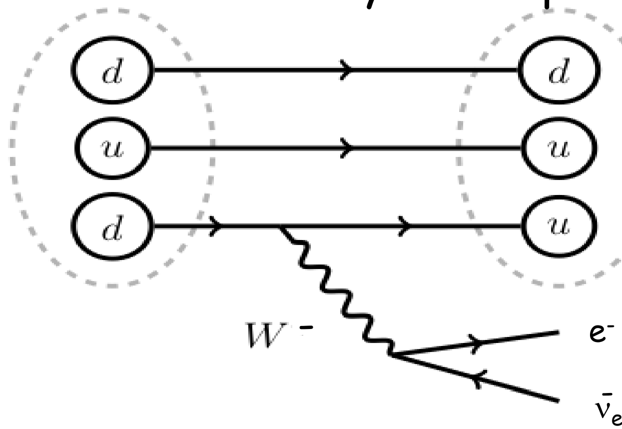
Multiplets of barions made of u,d, s and c quarks

Feynman diagrams for the Weak interaction

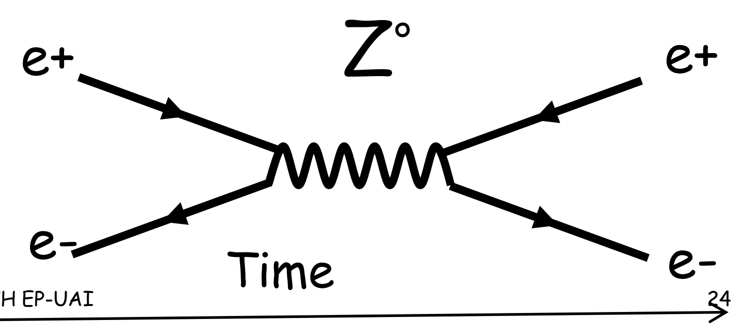
The diagrams are useful to calculate the interaction probability in one vertex

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

neutron decay into a proton



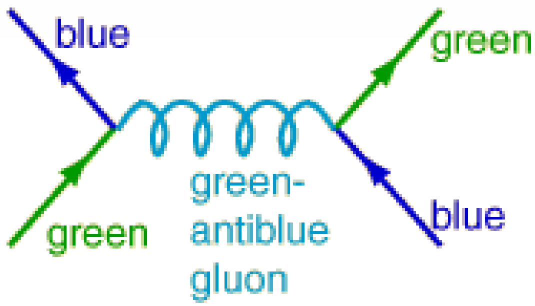
Z couples to:
Matter and antimatter versions of a fermion.



Feynman diagrams for the Strong and EM interactions

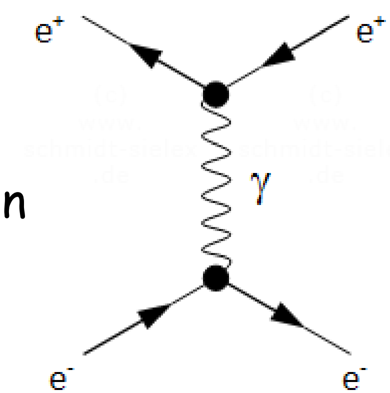
Strong interaction

Time



Gluon-mediated interaction between two quarks.

Electromagnetic interaction



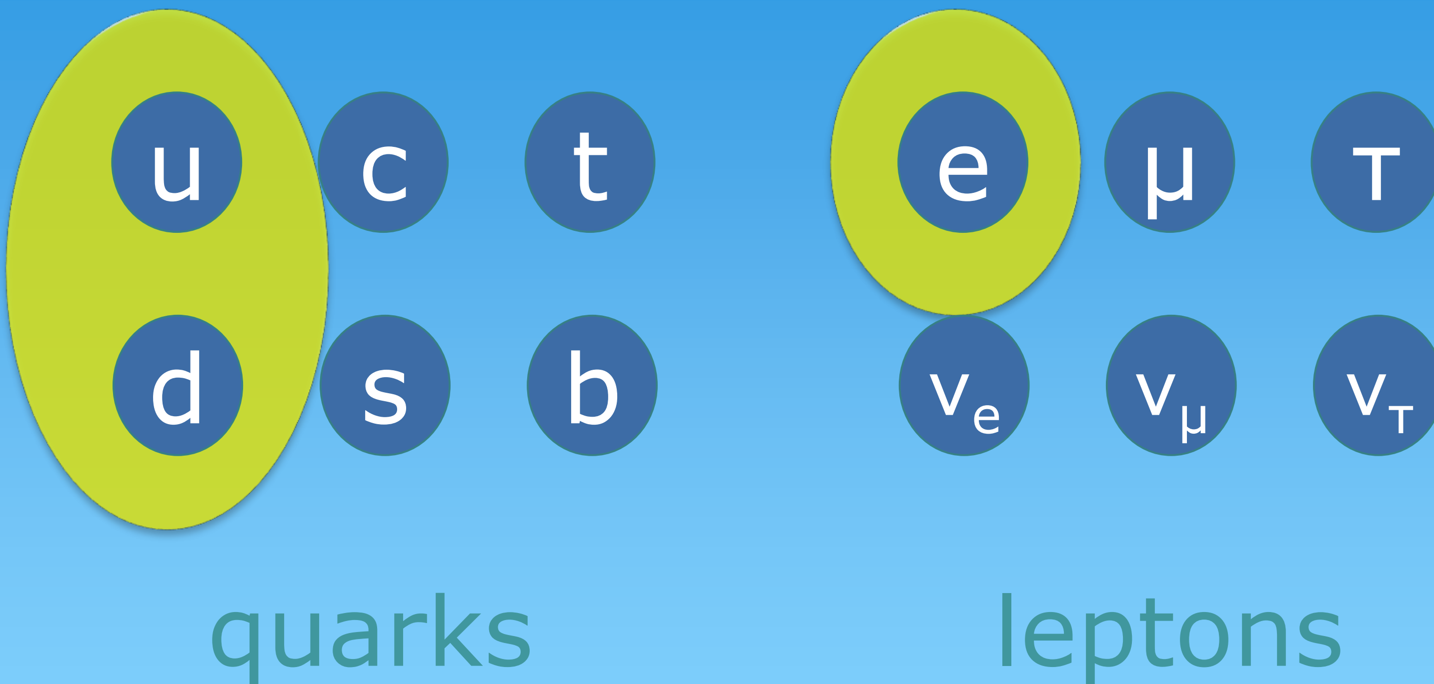
Time

A bit of history

u	c	t	e	μ	τ
d	s	b	ν_e	ν_μ	ν_τ

quarks

leptons

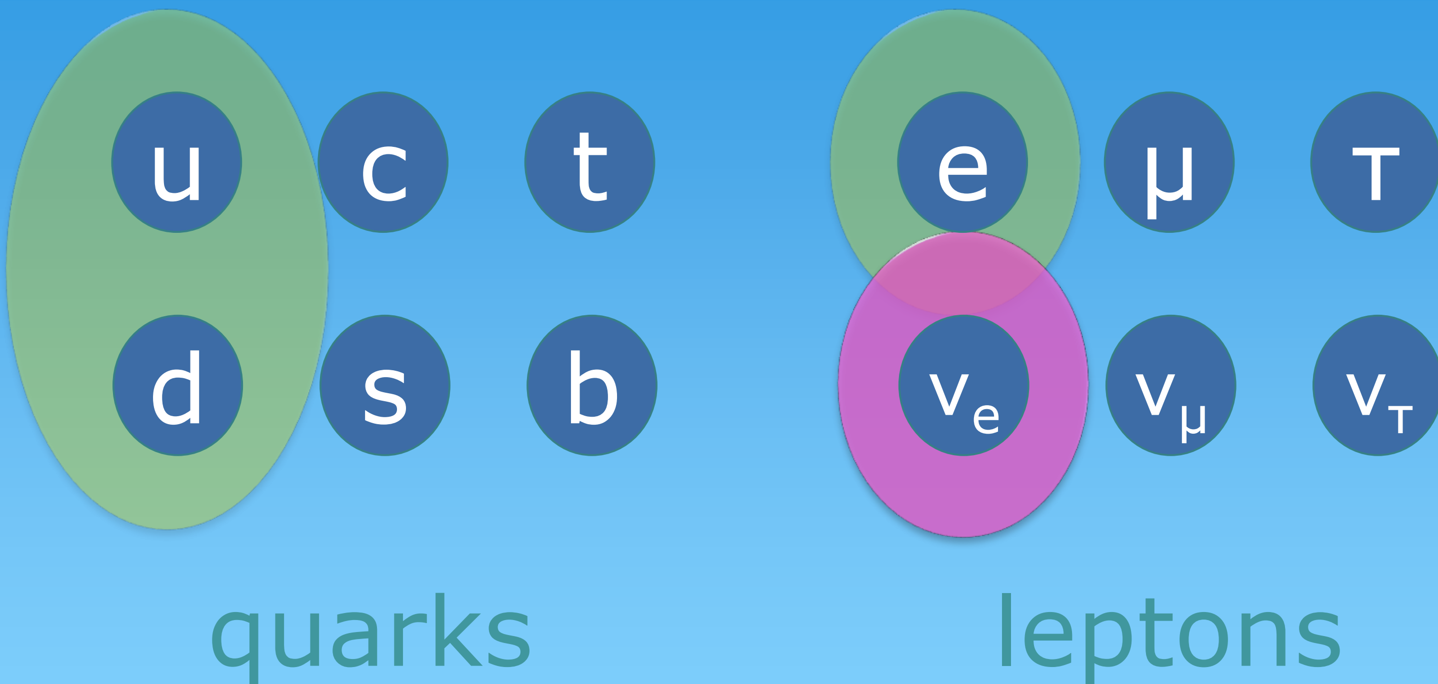


u,d proposed 1960s, discovered ~1968

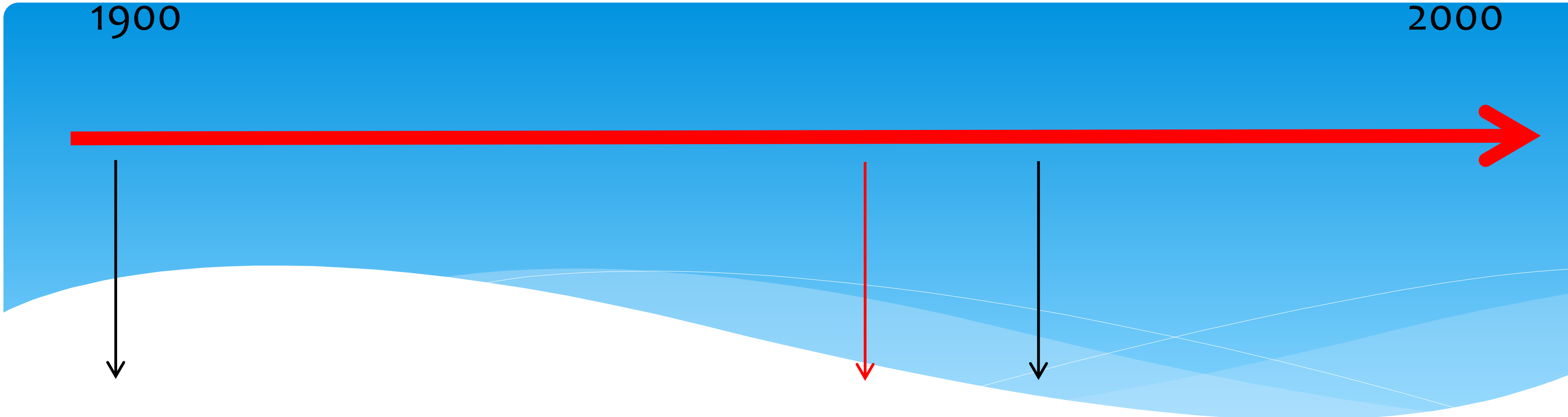
e discovered 1897

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

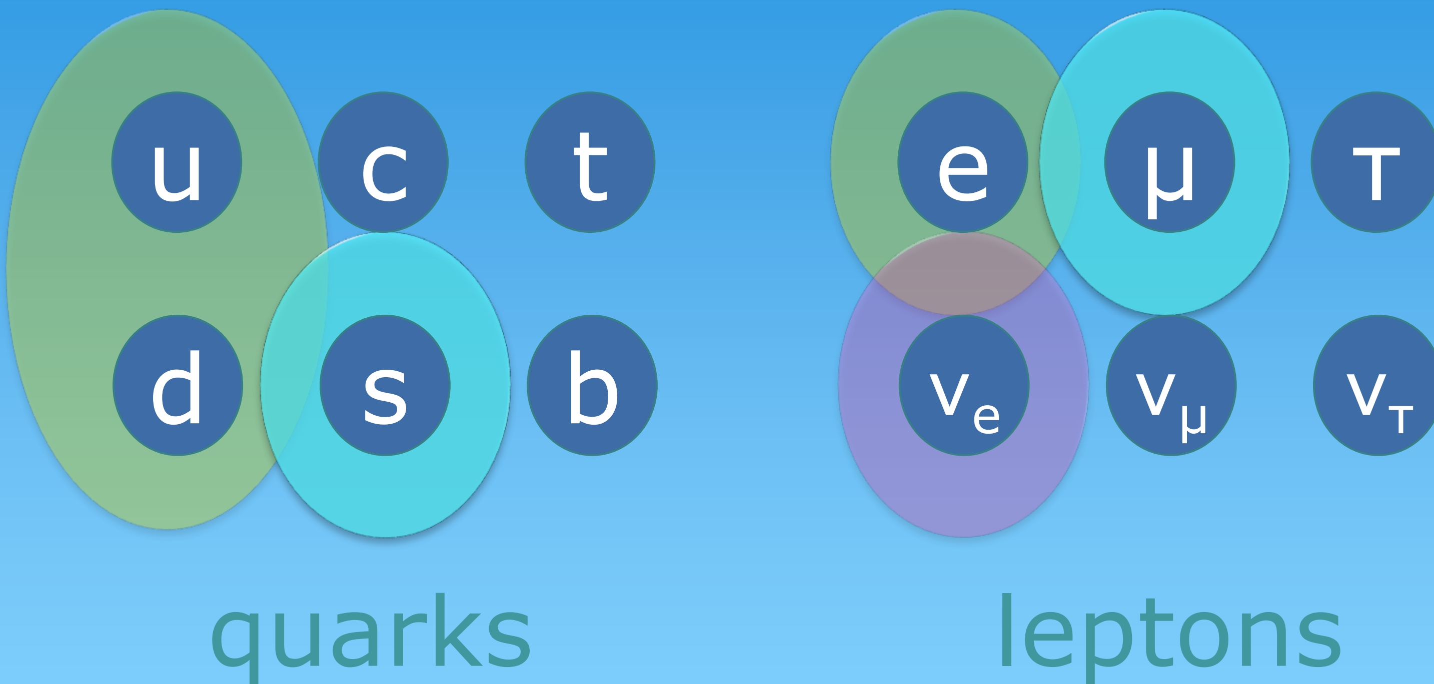
1969
up, down, strange quarks
E.D. Bloom *et al. Physical Review Letters* **23** (16): 930
J. M. Breidenbach *et al. Physical Review Letters* **23** (16): 235



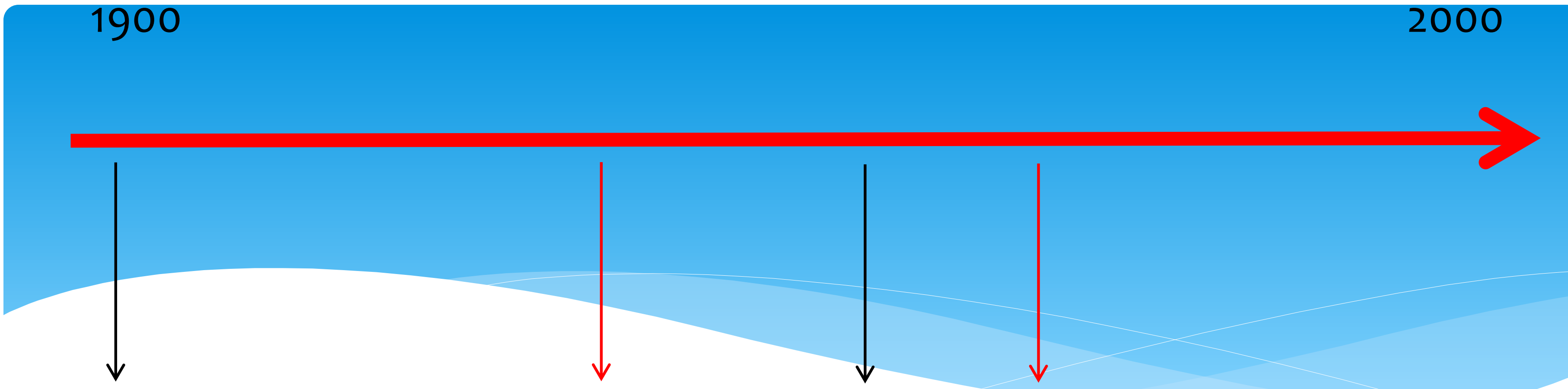
Radioactive decay (inferred 1930s, seen 1956)



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

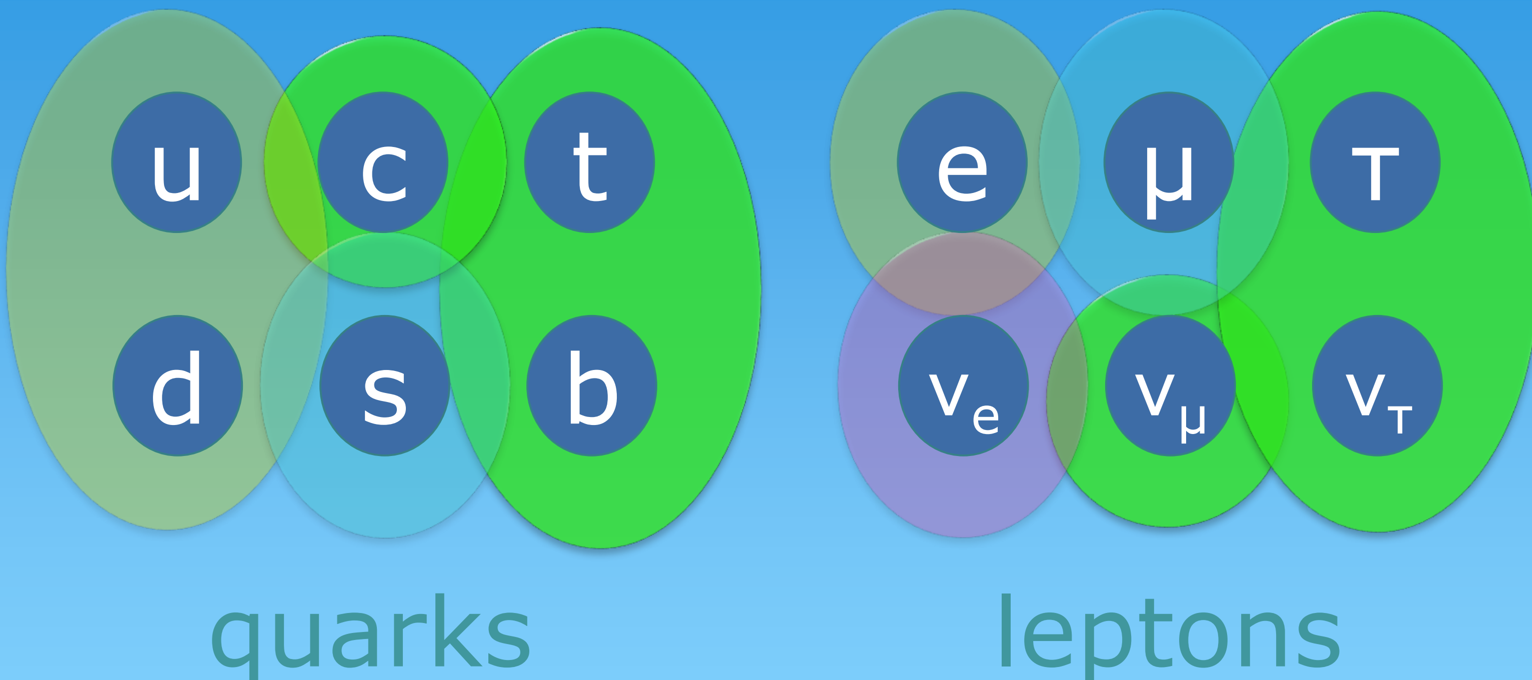


Cosmic ray experiments (1930s, 1940s)

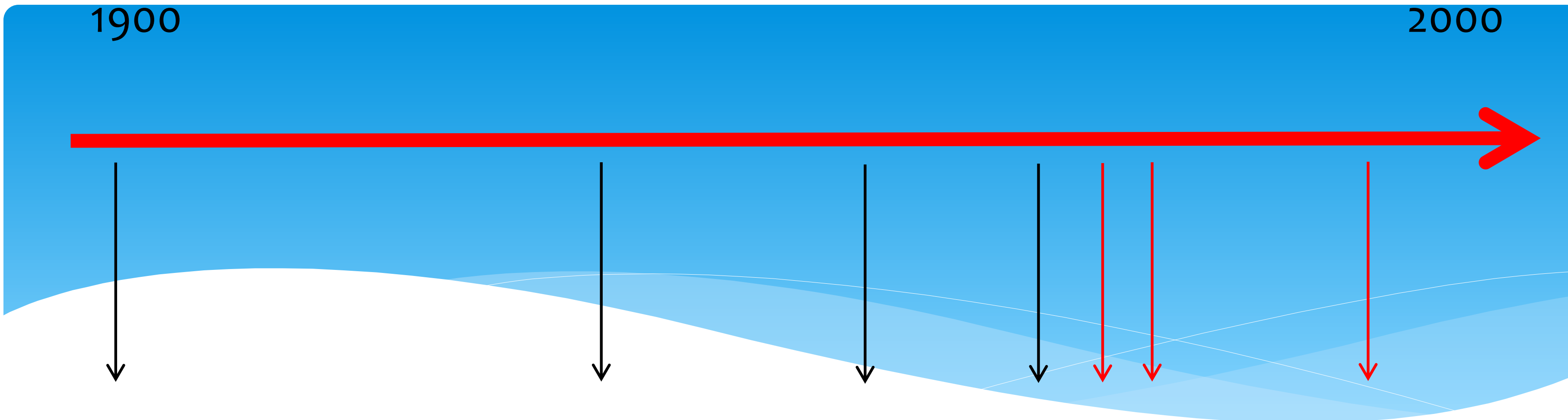


1937
Muon
S.H. Neddermeyer, C.D. Anderson, *Physical Review* **51** (10): 884

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



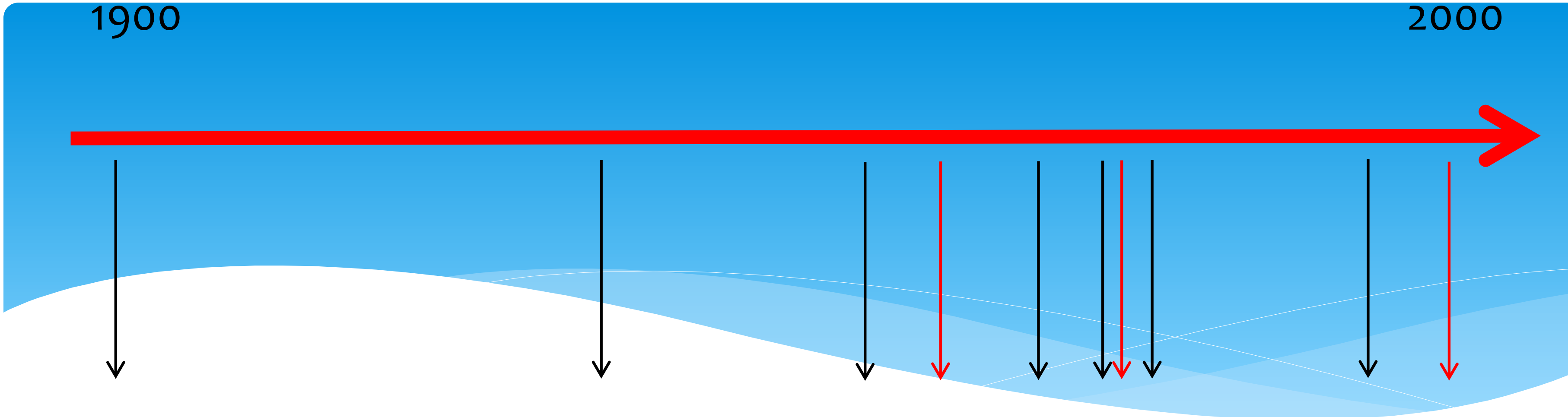
Collider experiments (1960s -)



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.

Summary Lecture I

- Particles are objects showing corpuscular-wave behavior (duality);
- Heisenberg's incertitude principle $\Delta x \Delta p \geq h$ and the minimum quanta of action h makes the classical mechanics inadequate for the description of the particle dynamic state . Quantum Mechanics is required (Lecture II)
- quarks and leptons (fermions, spin=$\frac{1}{2}n\hbar$) account for the visible mass in the Universe;
- Gauge bosons (spin=$n\hbar$) as force mediators of the three fundamental interactions: Electro-Weak and Strong;
- the quark model to simplify the particle zoo of mesons and baryons that are considered as composite particles;
- BEH field provides mass to the massive particles; observation of Higgs boson (spin=0) as confirmation of the BEH field existence (more in Lecture II).