Particle Physics of the early Universe

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Why do you need that?

What this course is about?

Beginning of the XXth century: 3 **independent** revolutions.

1. **Quantum Physics**

   attempts to explain atomic and nuclear physics, build not intuitive, but at least closed, complete and self-consistent theory.

2. **Relativity**

   describe propagation of light and its interaction with matter .

3. **Extragalactic astrophysics**

   Not all bright objects on the sky are stars!! Some are galaxies, as big as ours, but located much further!! Hubble (1923)

What this course is about?

All three directions develop quickly and interact with each other.

- **QM** + **Relativity**:
  Quantum matter interacts with light. Particles created in nuclear reactions can be relativistic $\Rightarrow$
  - Need QM description of light. Dirac (1927)
  - Need relativistic Quantum Mechanics. Dirac (1928)

- **General Relativity** – relativistic theory of gravity Einstein (1916) .

- In **Astronomy**: observing 18 galaxies allows to establish Hubble Law – the Universe expands! Hubble (1929)

  This is consistent with GR Einstein (1917)
  . Friedmann (1922)
  . Lemaitre (1927)

What this course is about?

- **QM** + **Relativity**:

  – Need QM description of light. Dirac (1927)
  – Need relativistic Quantum Mechanics. Dirac (1928)

- Special **Relativity**,
  a property of Maxwell equations, observed experimentally

  implies theoretical generalisation:

  applied to accelerated systems, gives rise to equivalence principle and **GR** – relativistic theory of gravity Einstein (1916) .

  GR predictions are confirmed **a posteriori**.

- **Astronomy**: Hubble Law – the Universe expands! Hubble (1929)

  This is consistent with GR Einstein (1917)
  . Friedmann (1922), Lemaitre (1927)

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- **Astronomy**: observing 18 galaxies allows to establish Hubble Law – the Universe expands! Hubble (1929)

  – This could be understood even in Newtonian cosmology!

  – GR: no static and stable homogeneous solution Einstein (1917) :-(
  – Systematically studied by Friedmann (1922) :-)
  – Found independently and related to Hubble Lemaitre (1927) :-))

- If Universe expands, does this mean that it was dense and hot at the beginning (Hot Big Bang)?

- No ! Only in Gamov (1947) the HBB model is introduced.
  In 1931 Lemaitre proposed the ”hypothesis of the primeval atom” that exploded and started the expansion of the Universe. But this is not HBB yet !!

- It took a long time before it was accepted !
  English astronomer Fred Hoyle is credited with coining the term ”Big Bang” during a 1949 BBC radio broadcast. It is popularly reported that Hoyle, who favored an alternative **”steady state”**cosmological model, intended this to be pejorative, but Hoyle explicitly denied this and said it was just a striking image meant to highlight the difference between the two models.

- Even in 1964 (the of the discovery of CMB) such great cosmologist as Zeldovitch considered that HBB ”can not be true”.

- Steady state was an attempt a la Einstein to save the stationary and ”eternal” Universe
- But even ”primeval atom” a la Lemaitre does not lead to Hot BB so easely!
- Compare Universe with a star. When it collapses too much it does not become too hot, but very dense – neutron star (this was Zeldovitch scenario)
- The difference comes from nuclear and particle physics that Gamov et al applied (in 1947 and later)
- He concluded that Universe was radiation dominated at some moment and this changes the picture!!

  We will discuss this in details in the lecture about primordial nucleosynthesis.

Partcile physics I: relativistic QED

- Let us consider therefore what happened in particle physics between 1920s and 1960s.

- Modern particle physics is based on the combination of QM, Maxwell theory of Electromagnetism and Relativity (the latter can be considered as a part of Maxwell theory, see e.g. two moving charges)
  and consequences of the combination
  (existence of anti-particles, polarisation of vacuum, screening of charges, scattering with changing number of particles, appearance of new, classically forbidden, interactions between particles etc).
  Discovery of positron Anderson (1932)

- All this is based on QM and can be (and was!) understood before quantum field theory in modern sense was developed.

  Debay, Heisinberg, Weiskopf, Landau, Paierls, Bohr, Bronstein etc.. 1929-1936

Particles physics II: New particles and interactions

- Nuclear physics, two types of nuclear physics phenomena: α-**decay** and β-**decay**

- Cosmic rays, first accelerators produced many new particles (positrons, muon, pions, ...)

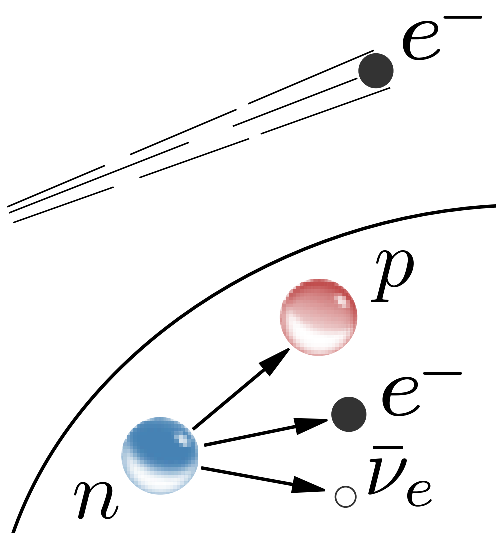
- These phenomena did not find their explanation in the framework of QED

From α–decay to strong interactions:

See timeline here: hep-ph/0001283

- Discovery of proton (1919)
- Discovery of neutron (1932)
- Lots of new particles (mesons, baryons)
- Classified according to representation of SU(2) and SU(3) group
- Baryons are composite: existence of quarks (1964)
- Color. Confinement
- Quantum Chromodynamics (QCD): theory of “strong interactions” (1973)

Fermi theory of β–decay [1]



- Neutron decay $n \to p + e^- + \bar{\nu}_e$
- Two papers by E. Fermi:

An attempt of a theory of beta radiation. 1. (In German) Z.Phys. 88 (1934) 161-177
DOI: 10.1007/BF01351864

Trends to a Theory of beta Radiation. (In Italian) Nuovo Cim. 11 (1934) 1-19
DOI: 10.1007/BF02959820

Continuum spectrum of electrons (**1927**)
Prediction of neutrino (**1930, 1934**)
Fermi theory (**1934**)
Universality of Fermi interactions (**1949**)

- Fermi 4-fermion theory:

$$V_{if} = G_F \tag{1}$$

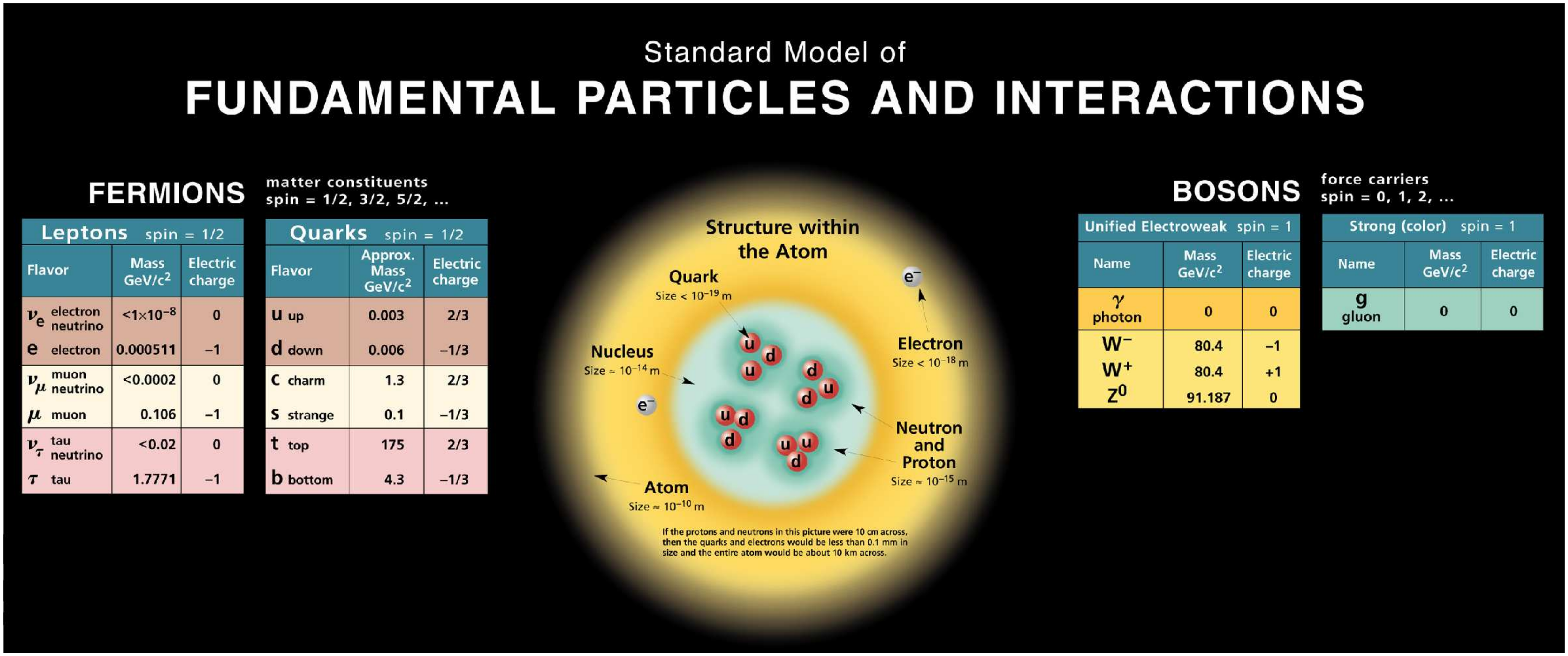
- New phenomenological constant, G_F, **Fermi constant**.

[0] History of β-decay (see **[hep-ph/0001283]**, Sec. 1,1); Cheng & Li, Chap. 11, Sec. 11.1)

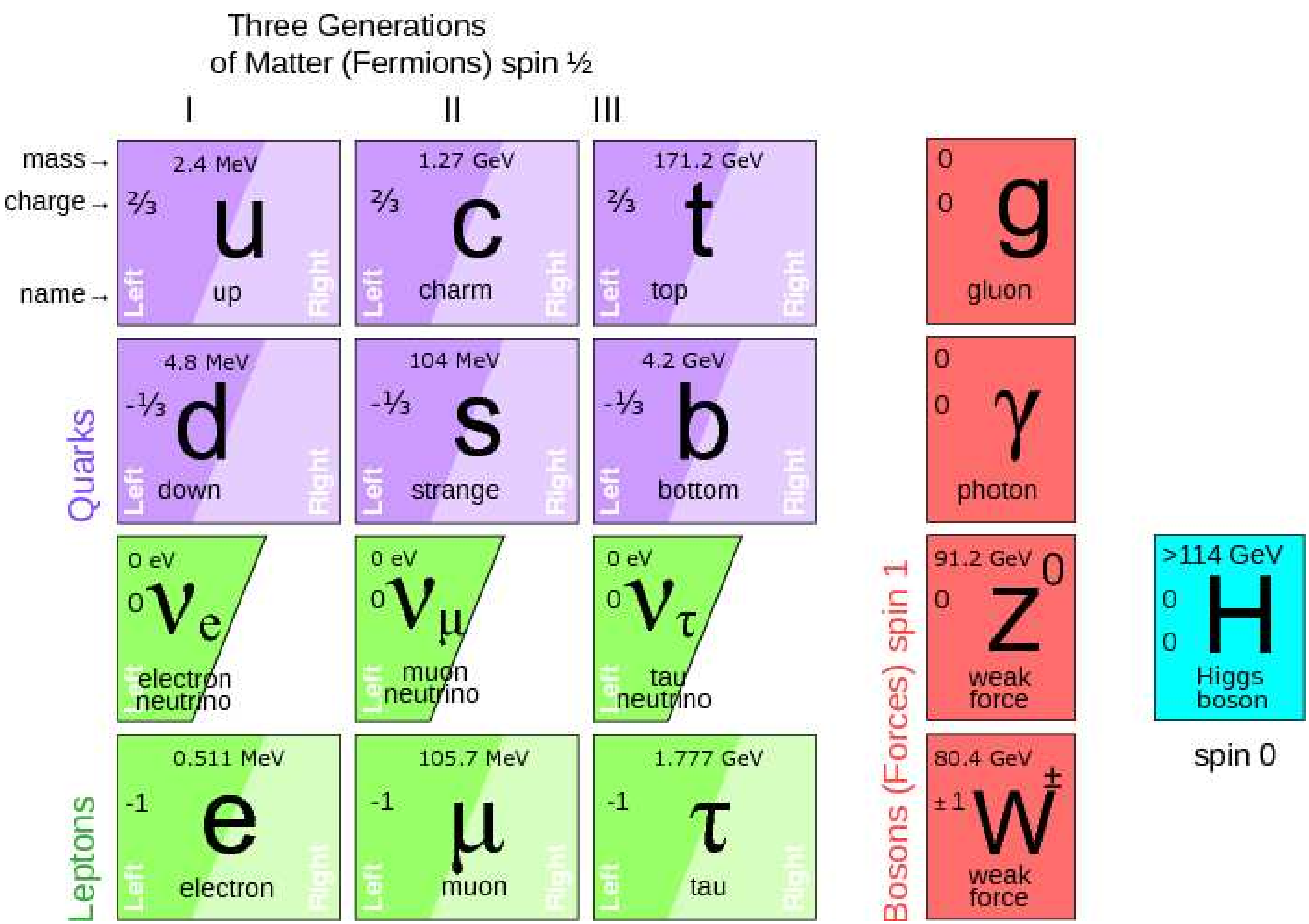
From β-decay to weak interactions

- Prediction of neutrino (1930)
- Discovery of positron (1932)
- Fermi theory (1934)
- Discovery of muon (1940)
- Parity violation (1955-1957)
- Theoretical problems with Fermi theory (1957) Prediction of massive vector bosons
- Electroweak theory. New gauge symmetries. (1964 – 1968)
- Discovery of neutral currents (1974)
- Discovery of Z and W bosnons, LEP (1980).

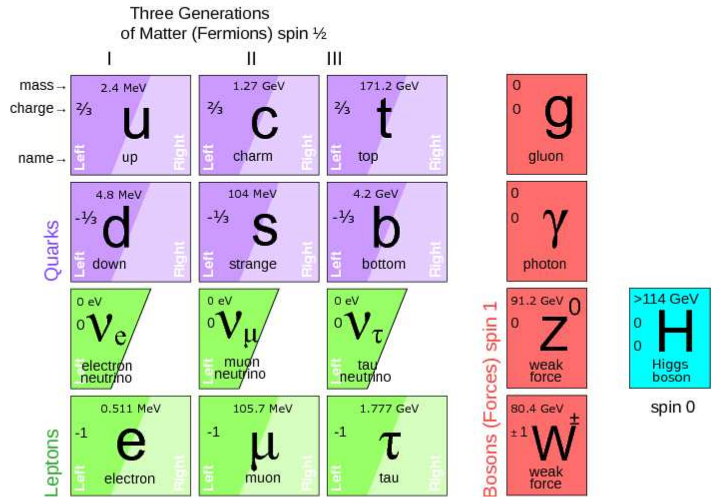
Standard Model: great success of particle physics



Standard Model



Standard Model



■ The Standard Model describes all the confirmed data obtained using particle accelerators and has enabled many successful theoretical predictions.

■ It has been tested with amazing accuracy, and its calculable quantum corrections play an essential role. Its only missing feature is a particle, called the Higgs boson, whose coupling to the other particles is believed to generate their masses.

HOWEVER WE UNDERSTAND NOW THAT THE STANDARD MODEL IS INCOMPLETE

Why to go beyond the Standard Model?

SM **does not explain** several phenomena in

- ◇ **Neutrino oscillations**: how the transition between the neutrinos of different flavors are explained?
- ◇ **Dark matter**: why observed gravity of galaxies and clusters is so strong?
- ◇ **Baryon asymmetry of the Universe**: what ensured that for each $\mathbf{10^{10}}$ anti-baryons there were $\mathbf{10^{10} + 1}$ baryon in the early Universe?

Phenomena beyond the Standard Model?

Cosmology

- **Inflation**: why universe is so large, old and homogeneous?
- What is the mechanism of the late-time **accelerated expansion** of the Universe (**dark energy**)?

Fine-tunning problems

- **CP violation in QCD**: Why do various CP violating effects in SM cancel so exactly?
- **Gauge hierarchy problem**: stability of the mass of the Higgs boson against quantum corrections

Hierarchy problem

Quantum corrections to the Higgs mass:

$$? \ \Downarrow$$

$$100 \text{ GeV} < M_H < 300 \text{ GeV}$$

$$\Uparrow$$

- Masses of fermions are provided by the Higgs field
- Fermion corrections to the Higgs mass are proportional to their mass M_f^2.
- Contributions from heavy fermions ($M_f \gg 100$ GeV) would make Higgs mass heavy $M_H \sim M_f$
- To keep Higgs boson light, one should **fine-tune** the parameters of the model to cancel fermions' contribution by that of Higgs