Large Hadron Collider (LHC) at CERN will soon start to operate

For several reasons – an extraordinary event:

First – its significance for the development of basic research in the physics of elementary interactions, structure of matter and cosmology.

Second – a rare example of extremely successful international, worldwide, scientific collaboration.

Finally, the event is extraordinary from our local, Polish perspective

A TURNING POINT
IN
THE PHYSICS OF
ELEMENTARY INTERACTIONS

Elementary interactions, structure of matter and the history of the Universe – a very old branch of physics

Fascinating continuity and evolution in time of its questions and goals

But its basic purpose remains unchanged over centuries: understand the structure of matter and its interactions at shorter and shorter distances

The history of this research is full of fundamental discoveries „by chance", misleading tracks, etc, but finally with spectacular successes.

Now we are at 10^{-18} m!
With LHC we shall probe 10^{-19} - 10^{-20} m

Izaac Newton – a pioneer in physics of elementary interactions:

- codified gravitational interactions by formulating the general law of gravitation

- introduced the notion of mass as the inertia parameter in the second law of dynamics

But the primordial origin of mass remained to be a great puzzle!

What is the origin of the mass of the electron?

Newton and the LHC – surprising link!

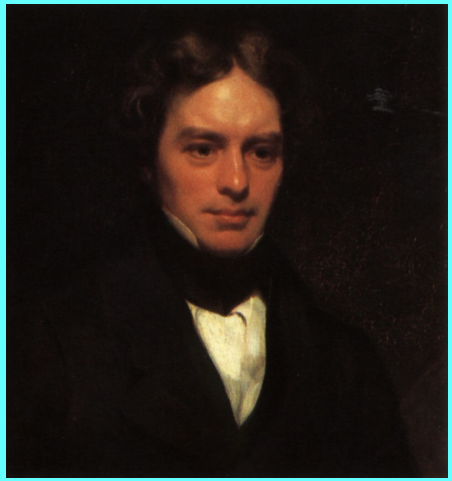
Electromagnetic interactions: decades of research

….

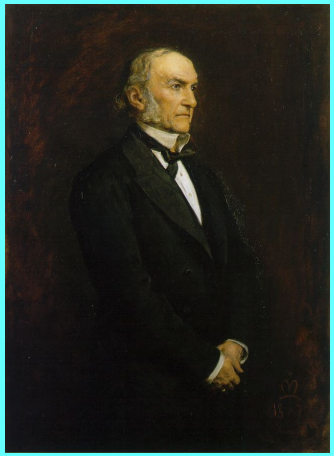
….

Michael Faraday (1791-1858) – concept of electromagnetic field

James Maxwell (1831-1879) – unified theory of electric and magnetic interactions: theory of electromagnetism



Michael Faraday
(1791 – 1858)



William Gladstone
(British politician –
future Prime Minister)

G: *What use is electricity?*

F: *One day Sir you may tax it.*

Taken from Ch.Llewellyn Smith,
The use of basic science

British scientists 1867

„Although we cannot say what remains to be invented, we can say that there seems to be no reason to believe that electricity will be used as a practical mode of power.”

New chapter in the physics of elementary interactions - discovery of radioactivity

XIX / XX; Henri Becquerel, Maria Skłodowska-Curie, Pierre Curie, Ernest Rutherford: discovery of α and β rays

Later understood as two new types of interactions

– weak interactions

– strong interactions

exist only at quantum level

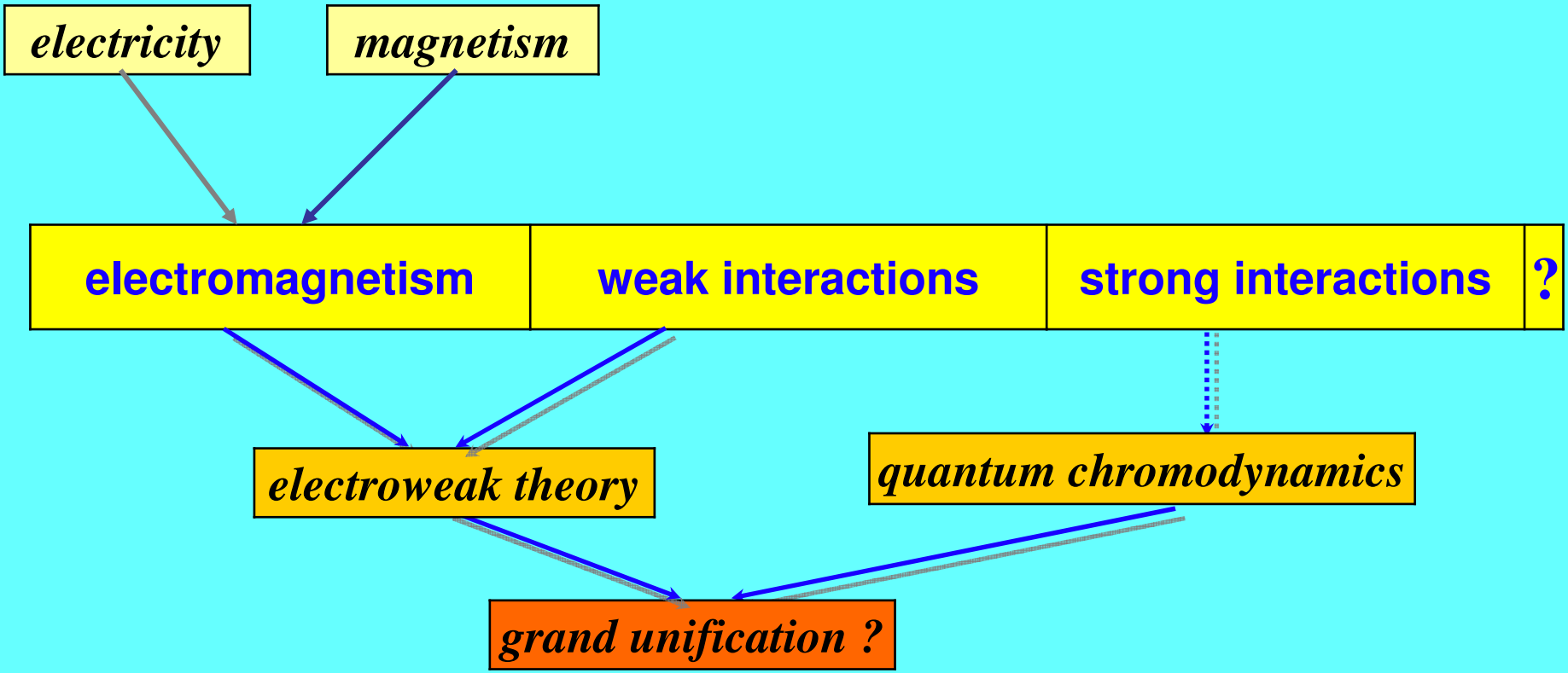
Gravity, electromagnetism, weak and strong interactions – this is the list of elementary interactions up to date

After one century of research, the chapter opened by the discovery of radioactivity is now closed.

We understand electromagnetic, weak and strong interactions – a fantastic theory termed the Standard Model of elementary interactions

The underlying principle is quantum physics; quantum field theory, with its duality of particles and fields.

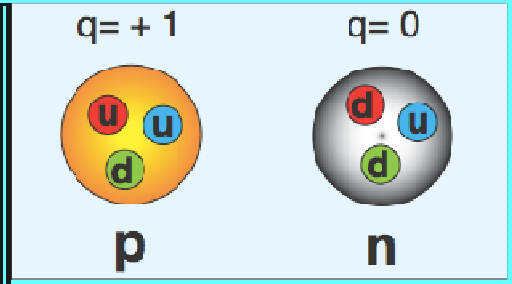
Unification



The elementary constituents of matter

„Matter particles": fermions

particles (charge)			
$e\ (-1)$	$\nu_e\ (0)$	$u\,u\,u\ (\frac{2}{3})$	$d\,d\,d\ (-\frac{1}{3})$
$\mu\ (-1)$	$\nu_\mu\ (0)$	$c\,c\,c\ (\frac{2}{3})$	$s\,s\,s\ (-\frac{1}{3})$
$\tau\ (-1)$	$\nu_\tau\ (0)$	$t\,t\,t\ (\frac{2}{3})$	$b\,b\,b\ (-\frac{1}{3})$

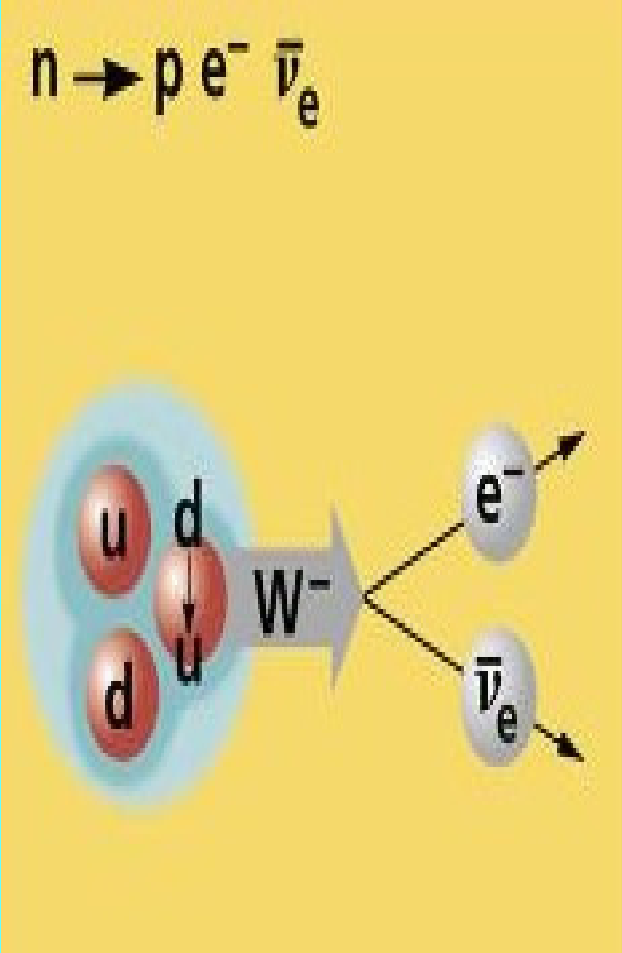


+ antiparticles

Interaction particles: bosons

Interaction	Range	Elementary particles (bosons)
electromagnetism	∞	photon
weak interactions	$\sim 10^{-18}$ m	W^+, W^-, Z
strong interactions	$\sim 10^{-15}$ m	8 gluons

Radioactive β decay is finally understood – in the Standard Model it is closely connected to electromagnetic interactions



Analogy to photon exchange: the difference is that W particles are very heavy

Vacuum" is not empty: it is filled with the Higgs field and interaction with it is the source of W mass; photon does not interact with the Higgs field.

Quarks and leptons interact with the Higgs field and get masses

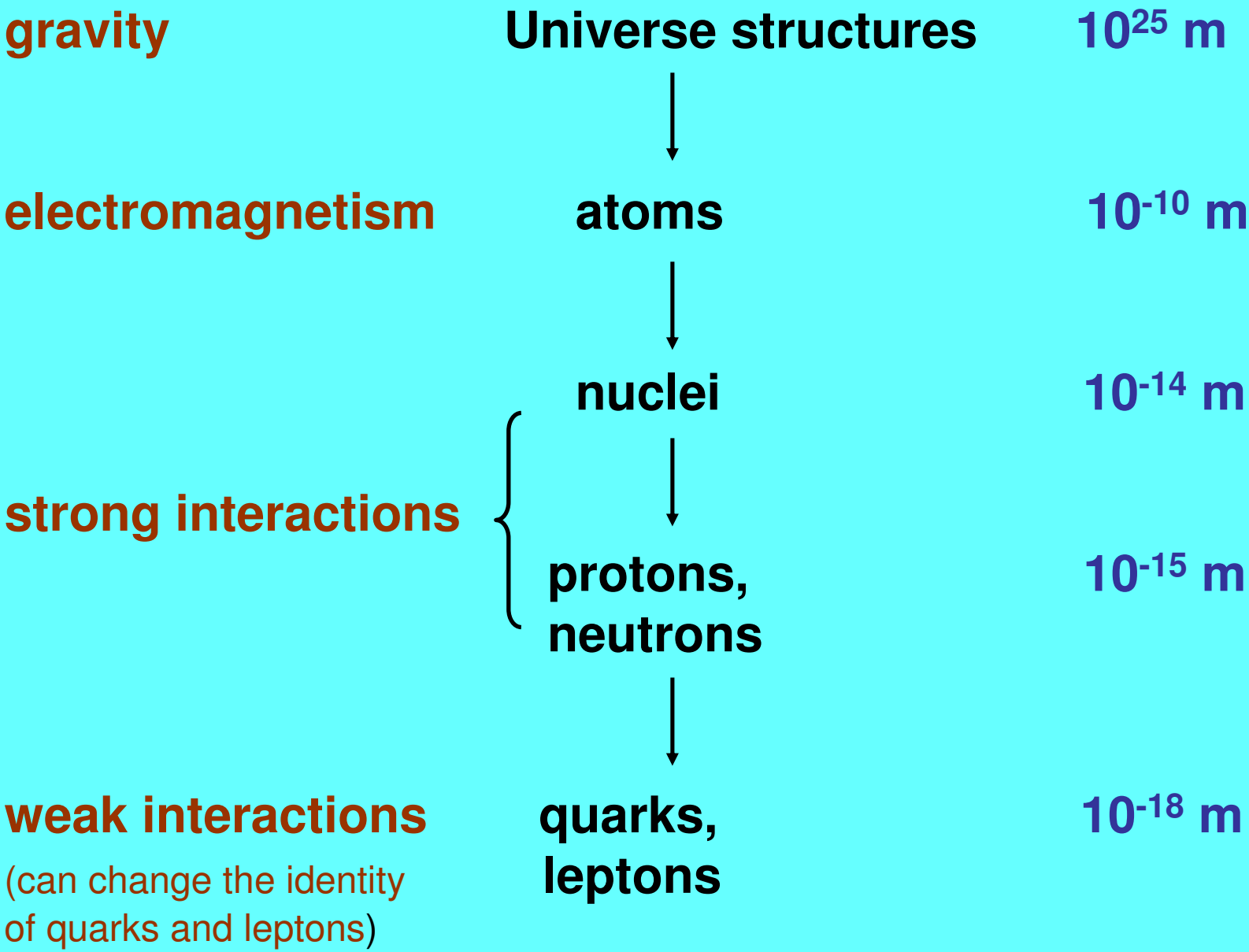
Fifth interaction – with the Higgs field?

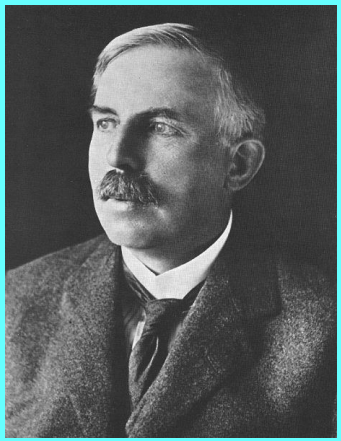
– solves the „mass problem” left behind by Newton?

– to be confirmed by the LHC!

Two comments:

– close link of elementary interactions with the structure of matter


gravity
Universe structures
10^{25} m
electromagnetism
atoms
10^{-10} m
nuclei
10^{-14} m
strong interactions
protons,
neutrons
10^{-15} m
weak interactions
(can change the identity
of quarks and leptons)
quarks,
leptons
10^{-18} m



Ernest Rutherford discovered atomic nuclei (1911)

„Anyone who expects a source of power from the transformation of atoms is talking moonshine"

– **moving in time front-line research in physics of elementary interactions leaves behind more specialized new branches of physics, with their impact on other sciences and/or applied research**

electromagnetism → atoms → atomic physics
(condensed matter physics, chemistry, biology, applications)

strong interactions → nuclei → nuclear physics
(nuclear energy, isotopes,…)

→ protons, neutrons
(medicine)

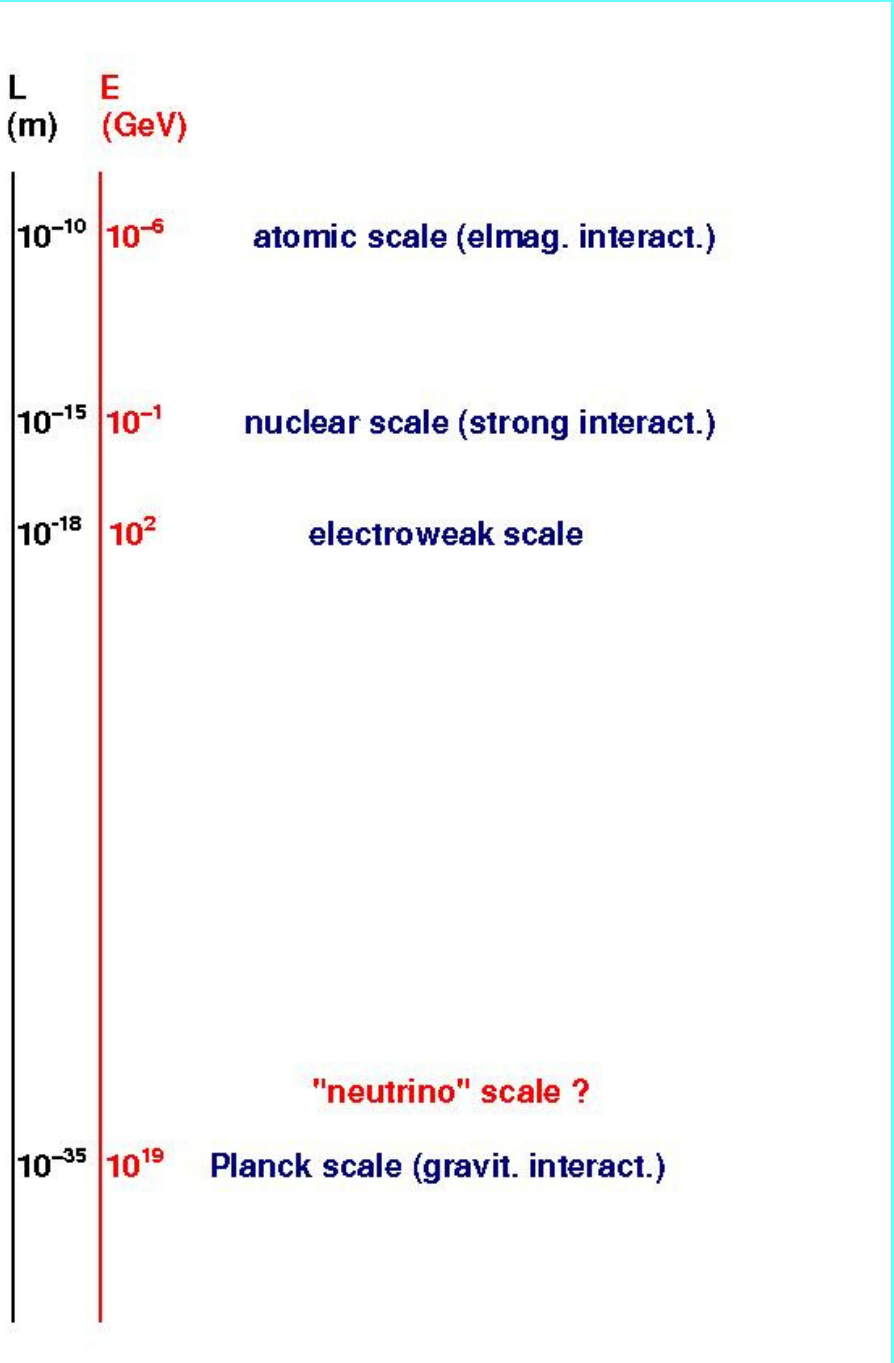
Standard Model → cosmology

The chapter is closed but….
is the Standard Model
the Theory of Everything?

Extremely unlikely!

Theoretical arguments – hierarchy of scales in physics

Empirical arguments – from cosmology


L
(m)
E
(GeV)
10^{-10}
10^{-6}
atomic scale (elmag. interact.)
10^{-15}
10^{-1}
nuclear scale (strong interact.)
10^{-18}
10^{2}
electroweak scale
"neutrino" scale ?
10^{-35}
10^{19}
Planck scale (gravit. interact.)

The Standard Model can be theoretically consistent only if there is new structure (new length scale) close to the weak scale or no new scale at all….

But gravity, neutrino masses….

Very high new scales make Standard Model inconsistent

Elementary interactions and cosmology

– paradoxical connection?

Length scales:

structure of matter known down to 10^{-18} m

the size of the Universe – 10^{25} m

Elementary interactions and the history of the Universe

Basic empirical fact: the universe expands

In the remote past, it was very small and very hot. Particles present in the universe were colliding with enormous energies

The undergoing processes were consequence of the laws of physics of elementary interactions

Interactions and matter constituents so far discovered and described by the Standard Model explain only part of the observed Universe (formation of nuclei and atoms)

But in our Universe
- **there is no antimatter**
- **there is a lot of „dark matter”**

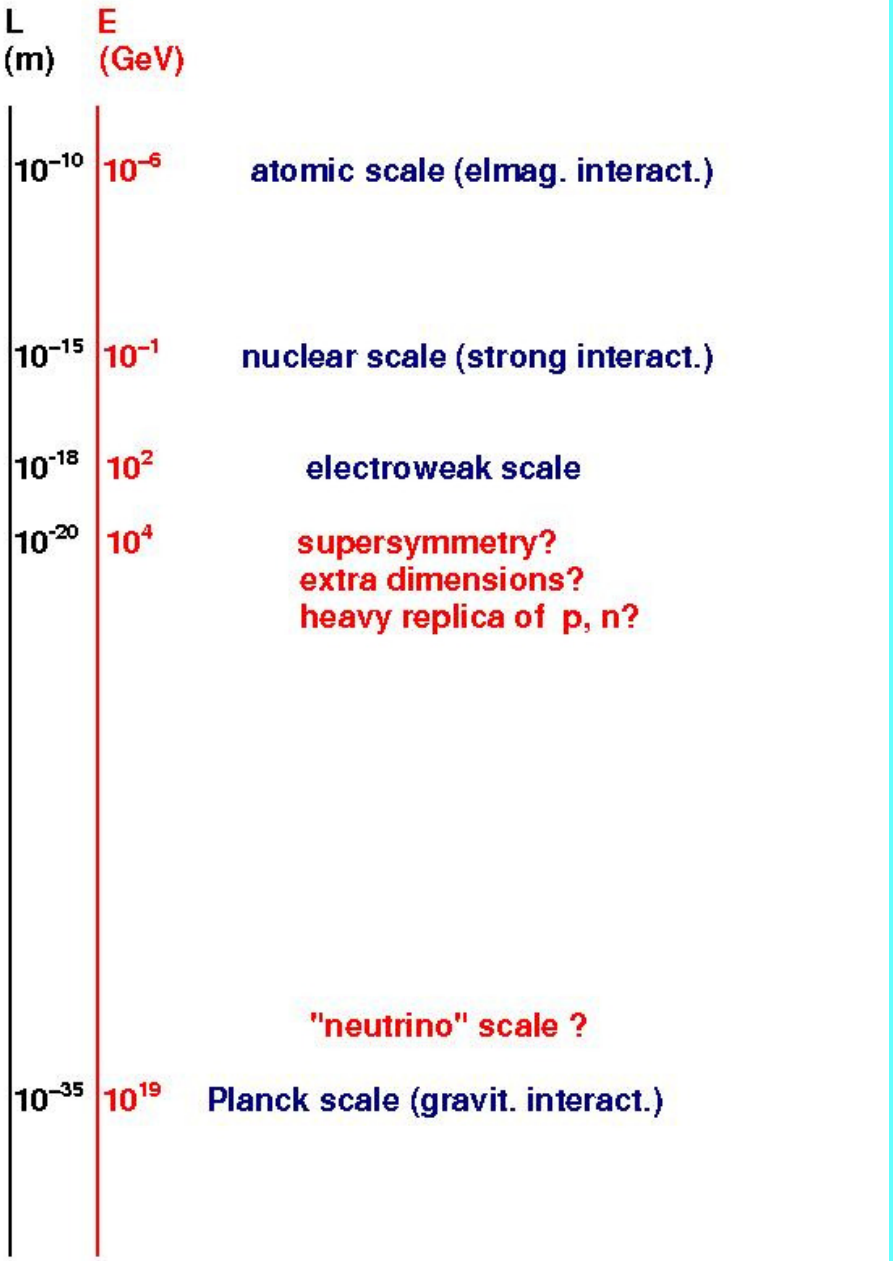
Both facts require the existence of
- **new forms of matter**
- **new interactions**

A turning point of the physics of elementary interactions – one chapter closed but…

We are convinced the structure of matter has still a deeper layer going beyond the SM

But how does it look like?

- **Supersymmetric world ?**
- **More than 3 dimensions of space? (Newton's and Einstein's gravity has to be „corrected"?)**
- **New world of new strong interactions, heavy replica of protons, neutrons etc?**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nuclear scale (strong interact.)
10^{-18}
10^{2}
electroweak scale
10^{-20}
10^{4}
supersymmetry?
extra dimensions?
heavy replica of p, n?
"neutrino" scale ?
10^{-35}
10^{19}
Planck scale (gravit. interact.)

Contrary to certain continuity of research that led to the formulation of the SM, except for the expected Higgs particle, we do not know which one of the ideas proposed for physics beyond the SM (or some of their variants ?) is correct.

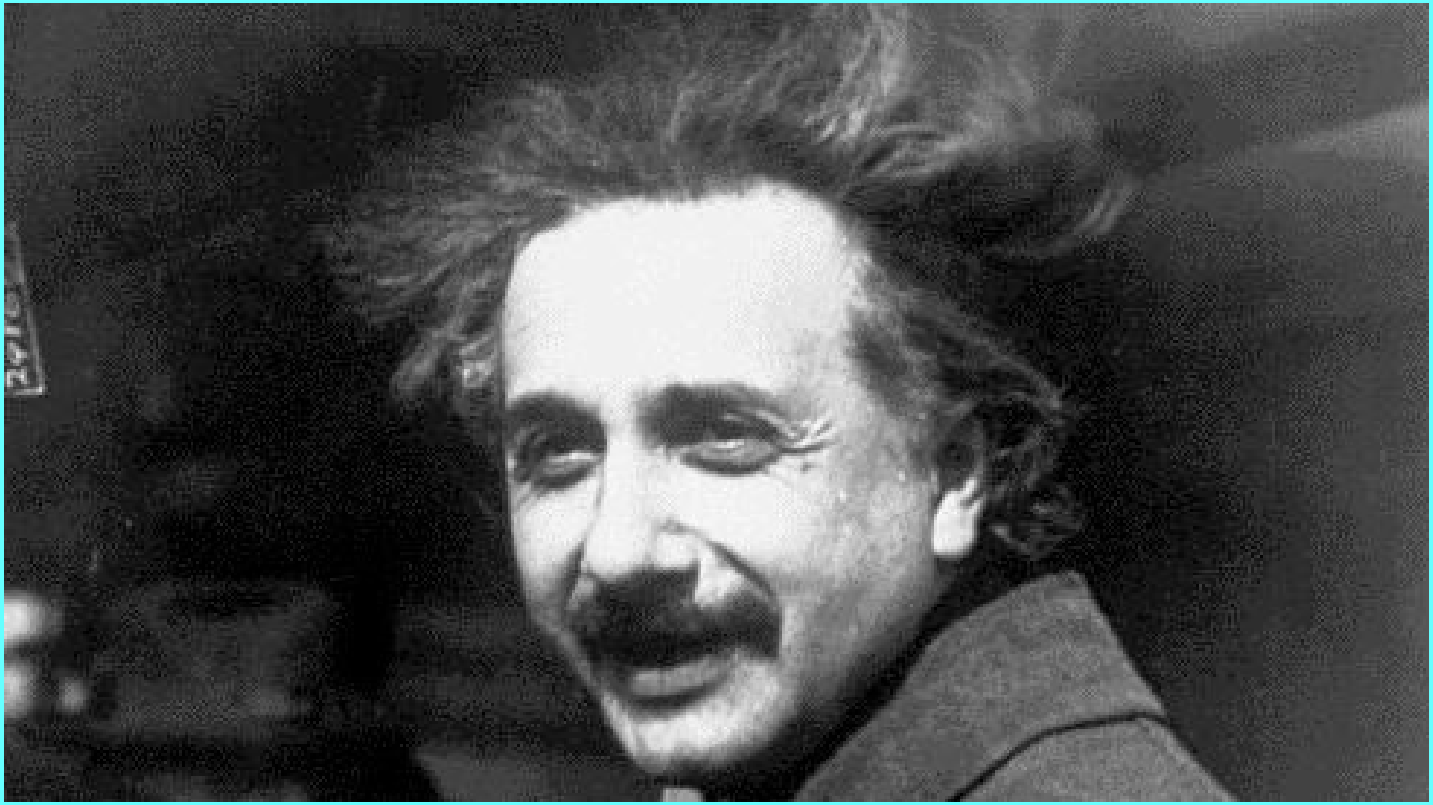
For many decades, the situation in particle physics has not been as intriguing as now, waiting for the outcome of the LHC experiments.

And time to think beyond the LHC!

Robert R.Wilson
– first Director of Fermilab in Batavia

Congressional Committee:
What will your lab contribute to the defense of the US?

Wilson:
Nothing, but it will make it worth defending.



Everything should be made as simple as possible, but not simpler

END