Part I

Part I

Discoveries for physics revolutions

Part II

Introduction to the Standard Model of Particle Physics

Part III

Beyond the SM: SUSY and ToE

A romantic dream for an unified description of the universe?

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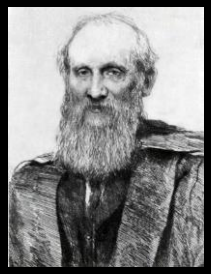
PREFACE

This is a lecture about 100 years of particle physics.
It covers about 100 years of ideas, theories and experiments.

More than 50 Nobel prize winners on particle physics
This is a broad overview about the main discoveries with dissertations on the future trends.

In the early 1900s, most physicists believed that physics was complete, described by the Newton's mechanics and gravity, thermodynamics, and the Maxwell theory.

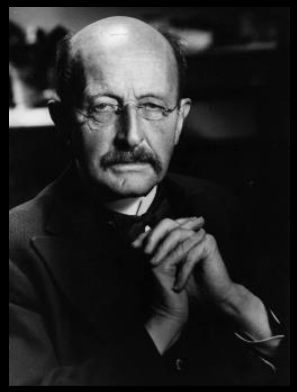


Lord Kelvin

"There is nothing new to be discovered in physics now. All that remains is more and more precise measurement. " (Lord Kelvin, 1900)

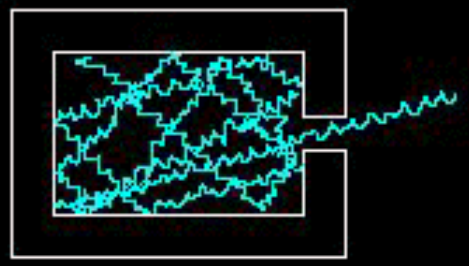
DARK CLOUDS:
1) Blackbody radiation - Quantum Physics
2) Michelson-Morley experiment - Special Relativity

ENERGY COMES IN QUANTA



M. Planck

1900: ELECTROMAGNETIC RADIATION IS EMITTED IN QUANTA



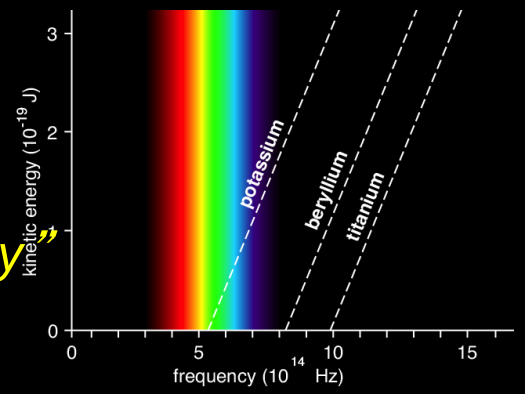
$$\varepsilon = h\nu$$

$$I(n) \sim n^2 \frac{hn}{e^{\frac{hn}{kT}} - 1}$$

P. von Lenard

1902: PHOTOELECTRIC EFFECT

"The electron energy does not show the slightest dependence on the light intensity"



A. Einstein

1905: LIGHT IS EMITTED AND ABSORBED IN QUANTA

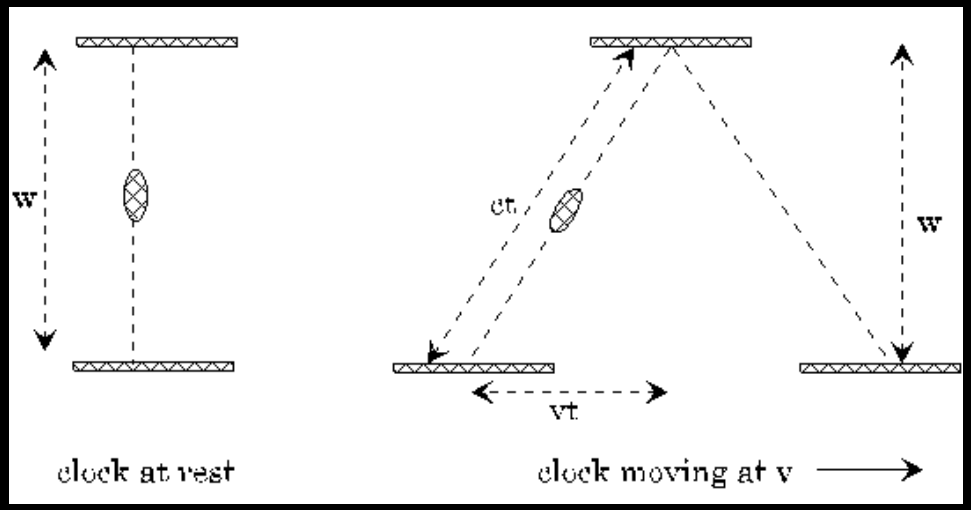
$$E_{max} = h\nu - W$$

"My only revolutionary contribution to physics"

SPECIAL RELATIVITY

A. Einstein

1905: SPEED OF LIGHT IS ALWAYS CONSTANT



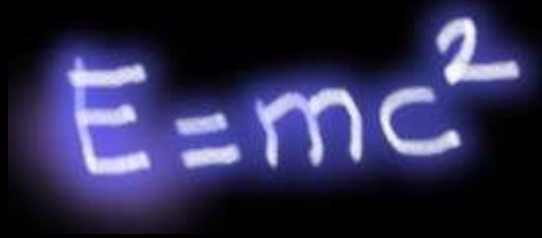
$$c^2t^2 = v^2t^2 + w^2$$

$$t = \frac{w/c}{\sqrt{1 - \frac{v^2}{c^2}}} = g \times t$$

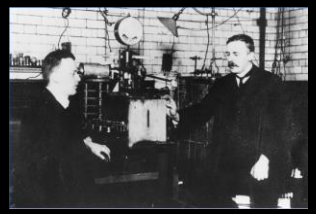
1) Time dilation, space contraction

2) Modification of Newton's laws, relativistic mass increase

3) From space and time to the 4-dimensional space-time of Minkowski



THE BEGINNING OF ATOMIC PHYSICS



Rutherford

1909: NUCLEI: very small + heavy within (almost) empty atom

Hydrogen

1913: BOHR MODEL- (empirical) explanation of discrete spectral lines

(using Planck's constant h) to quantize angular momentum

L. de Broglie

1923: DE BROGLIE

Particles are (also) waves

Photons behaves (also) as particles

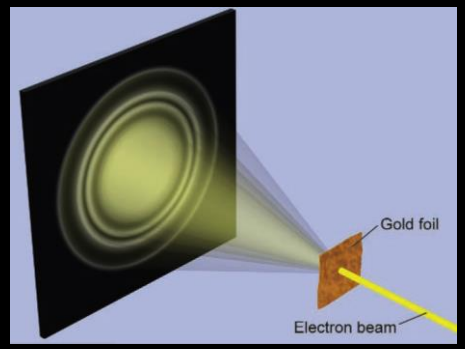
Compton scattering

(particle-wave duality)

Complementarity

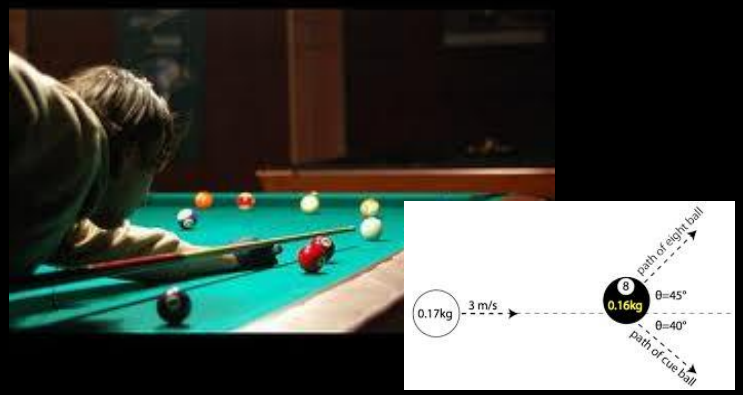
$$p = h/\lambda$$

$$E = h\nu$$



Classical Mechanics

Classical Mechanics: simultaneous measurements of observables don't perturb the system state. Reformulating the Newton's mechanics by the Lagrangian or Hamiltonian the equation of motion can be obtained.



Hamilton's equations

H=T+V

$$\dot{\mathbf{p}} = -\frac{\partial H}{\partial \mathbf{q}}, \quad \dot{\mathbf{q}} = +\frac{\partial H}{\partial \mathbf{p}},$$

Lagrange's equations (1788)
L=T-V

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_j}\right) = \frac{\partial L}{\partial q_j}$$

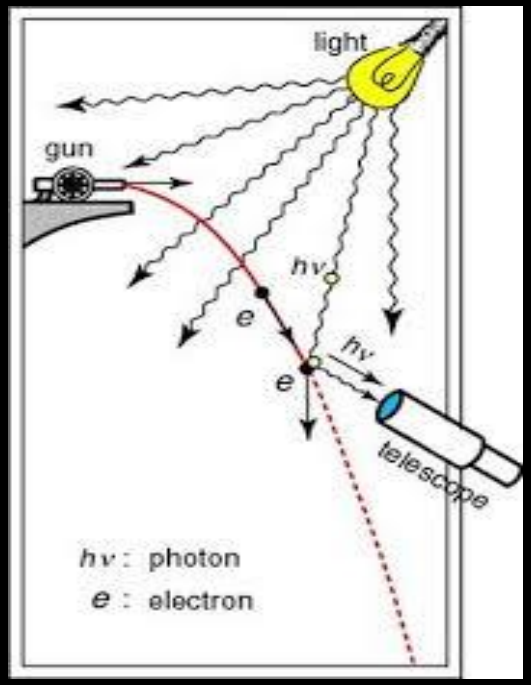
H or L symmetries (invariance): the study of the invariance of H or L (same form and value) under:

1) coordinate translation → momentum conservation;
2) reference system rotation → angular momentum conservation;
3) time translation → energy conservation;
4) Lorentz transformation→ relativistic invariance;

represents the basis for the future development of Quantum Mechanics.

Classical Mechanics : inadequate for the atomic physics)

Quantum Mechanics: particle-wave duality implies mathematical operators to extract E, $\vec{p}$,.. values from state wave functions. The measurement act perturbs the system state.



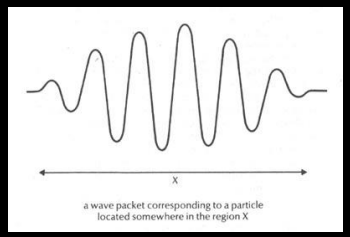
QUANTUM MECHANICS

Heisenberg

1923: UNCERTAINTY PRINCIPLE

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

$$\Delta E \Delta t \geq \hbar$$



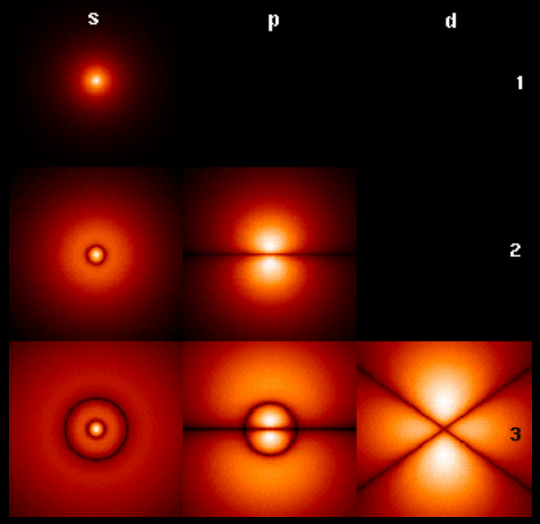
Schrödinger

1926: SCHRÖDINGER EQUATION

Hamiltonian operator

$$H\psi(\mathbf{r},t) = (T+V)\,\psi(\mathbf{r},t) = \left[-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{r})\right]\psi(\mathbf{r},t) = \mathrm{i}\hbar\frac{\partial\psi}{\partial t}(\mathbf{r},t)$$

(electrons in atoms form ‘standing waves’)



Interpretation (Born, 1927):

ψ = probability amplitude

∫ |ψ|2 dv = ∫(probability density) dv = 1

counterpart of motion equation of the classical mechanics.

RELATIVISTIC QUANTUM MECHANICS

Paul A.M. Dirac
(1928)

$$E^2 = p^2 + m^2 \rightarrow$$

$$E = \pm(\alpha \cdot p) + \beta m$$

$$(i\gamma^\mu \partial_\mu - m)\Psi = 0$$

$$\Psi = \begin{pmatrix} e^- \uparrow \\ e^- \downarrow \\ e^+ \uparrow \\ e^+ \downarrow \end{pmatrix}$$

Spin

Antimatter

CONSEQUENCES:

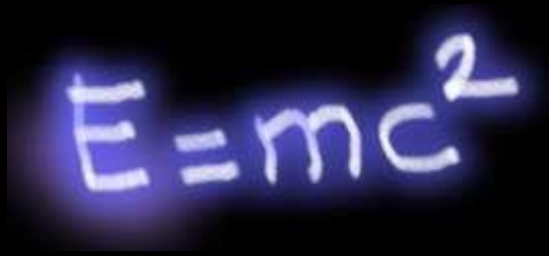
ELECTRON SPIN EXPLAINED
ANTIPARTICLES MUST EXIST !
ELECTRONS OBEY 'PAULI PRINCIPLE' (1940) - FERMIONS

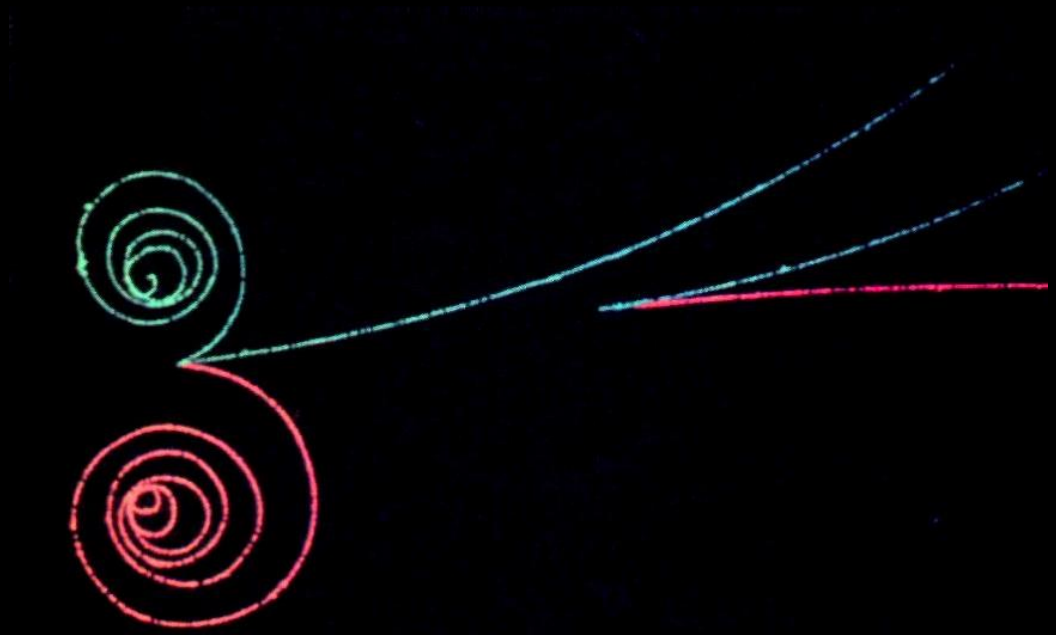
ANTIPARTICLES

Anderson

1932: POSITRON DISCOVERY

EVERY PARTICLE HAS AN ANTIPARTICLE





WHEN ENERGY CONVERTS TO MASS,
PARTICLES AND ANTIPARTICLES ARE PRODUCED

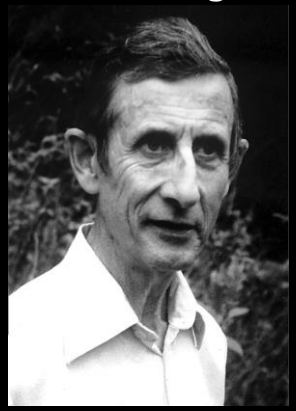
QUANTUM FIELD THEORY (1927 - 1948)

S.I. Tomonaga

It was known that the electromagnetic field consists of photons

J. Schwinger

How could the interaction between electrons and photons be correctly described, respecting quantum mechanics and special relativity?



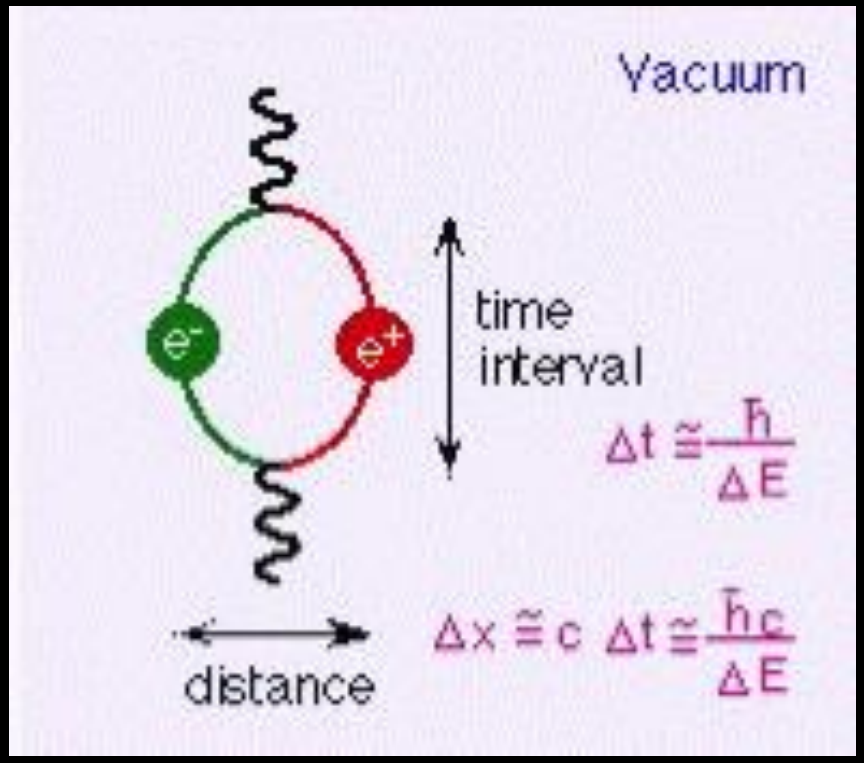
F. Dyson

Many people worked on this problem ...

EMPTY SPACE HAD BECOME COMPLICATED !

Quantum physics says that 'oscillators' (e.g. field quanta) cannot be at absolute rest (uncertainty relation)

The lowest energy states of e.g. electromagnetic fields can produce (virtual) electron-positron pairs: VACUUM FLUCTUATIONS



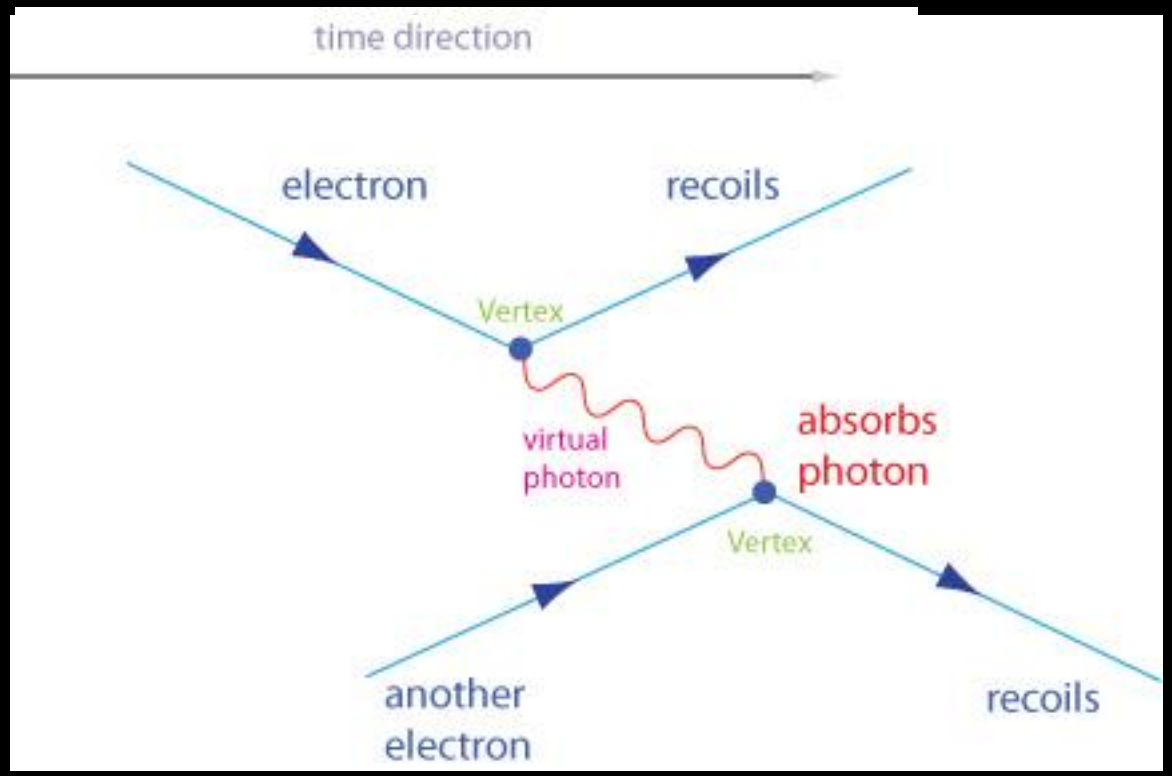
e.g. $\Delta t \cong 6.6\ 10^{-22}$ Mev.s/~1MeV $\cong 10^{-21}$ s

$\Delta x \cong 3 * 10^{8}$ m/s $* 10^{-21}$ s $\cong$ 300 fm

Quantum Electrodynamics (QED)

QED describe the EM interactions according to the QM+special relativity;
The photon is its gauge boson mediating the EM interaction.

R.P. Feynman

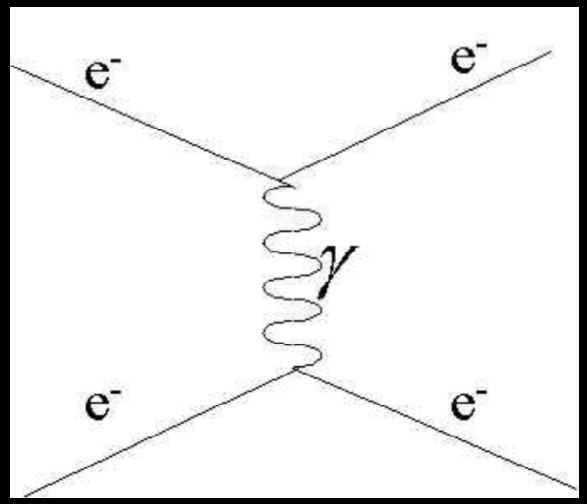


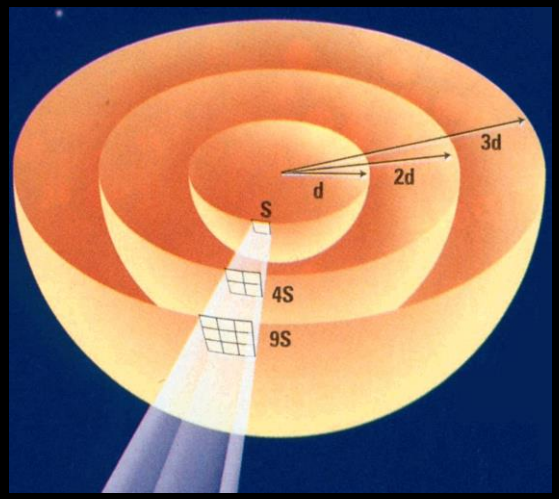
QED: Charged particles interact by exchanging photons

1) **Massless virtual photons are continuously emitted by electric charges**

2) The **$1/r^2$ law** comes from the probability to hit another particle at distance r

(directly connected with the 3 dimensions of space)





$1/r^2$ law

QED became a model for other interactions!

Summary part I

- Special relativity: c constant, space and time not constant, new 4-dimensions space-time by Minkowsky;
- Energy qunta hv, particle-wave duality λ=h/p,=> Quantum Mechanics (QM) with state (Ψ wave function) and observables (math. E, p Operators): Schrodinger eq;
- Special relativity + QM => Dirac equation => animatter and electron spin;
- QED: photon as field quanta, quantum vacuum as ground state of Maxwel EM field (virtual particles). QED: a succesful model, an example for the other interactions;