Search for hidden particles at SHiP. Lecture 1. Standard model. Problems of SM.

Volodymyr Gorkavenko
Taras Shevchenko National University of Kyiv

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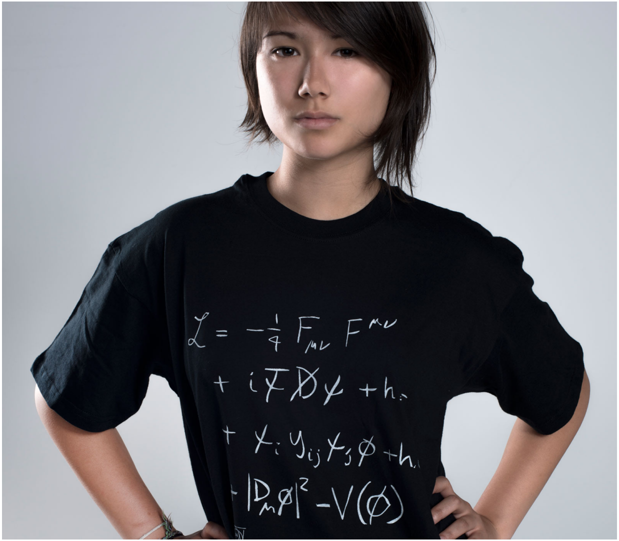
What is the SM?



UNFORTUNATELY, it is not Lagrangian of the SM !

This is Lagrangian of the SM

$$\mathcal{L}_{SM} = \sum_{\text{кварки}} \bar{q}(i\gamma^\mu\partial_\mu - m_q)q + \sum_n \bar{e}_n(i\gamma^\mu\partial_\mu - m_{e_n})e_n + \sum_n \bar{\nu}_n i\gamma^\mu\partial_\mu\nu_n +$$
$$+\frac{1}{2}\partial^\mu h\partial_\mu h - \frac{m_h^2}{2}h^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}Z_{\mu\nu}Z^{\mu\nu} + \frac{m_Z^2}{2}Z^\mu Z_\mu + m_W^2 W^{-,\mu}W_\mu^+ -$$
$$-\frac{1}{4}(\partial_\mu G_\nu^a - \partial_\nu G_\mu^a + g_s f^{abc}G_\mu^b G_\nu^c)(\partial^\mu G^{a,\nu} - \partial^\nu G^{a,\mu} + g_s f^{ab'c'}G^{b',\mu}G^{c',\nu}) -$$
$$-\frac{1}{2}\left[(\partial_\mu + ieA_\mu + ig\cos\theta_W Z_\mu)W_\nu^- - (\partial_\nu + ieA_\nu + ig\cos\theta_W Z_\nu)W_\mu^-\right] \times$$
$$\times\left[(\partial^\mu - ieA^\mu - ig\cos\theta_W Z^\mu)W^{+,\nu} - (\partial^\nu - ieA^\nu - ig\cos\theta_W Z^\nu)W^{+,\mu}\right] +$$
$$+\frac{g^2}{4}(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-)(W^{-,\mu}W^{+,\nu} - W^{+,\mu}W^{-,\nu}) -$$
$$-i\frac{g}{2}(F^{\mu\nu}\sin\theta_W + Z^{\mu\nu}\cos\theta_W)(W_\mu^- W_\nu^+ - W_\mu^+ W_\nu^-) +$$
$$+g_s \sum_{\text{кварки}} \sum_{a=1}^{8} \sum_{c,c'=r,g,b} \bar{q}_c \Gamma_{cc'}^{\mu;a} q_{c'} G_\mu^a + e\sum_f q_f \bar{f}_n \gamma^\mu f_n A_\mu -$$
$$-\frac{g}{2\cos\theta_W}\sum_f \bar{f}\gamma^\mu\left[t_3^f(1-\gamma^5) - 2q_f\sin^2\theta_W\right]f Z_\mu -$$
$$-\frac{g}{2\sqrt{2}}\sum_n\left[\bar{\nu}_n\gamma^\mu(1-\gamma^5)e_n W_\mu^+ + \bar{e}_n\gamma^\mu(1-\gamma^5)\nu_n W_\mu^-\right] -$$
$$-\frac{g}{2\sqrt{2}}\sum_{m,n}\left[\bar{u}_m\gamma^\mu(1-\gamma^5)V_{mn}d_n W_\mu^+ + \bar{d}_m\gamma^\mu(1-\gamma^5)V_{mn}^+ u_n W_\mu^-\right] -$$
$$-\frac{m_h^2}{2v}h^3 - \frac{m_h^2}{8v^2}h^4 - \sum_f \frac{m_f}{v}\bar{f}fh + \frac{2M_W^2}{v}W^{-,\mu}W_\mu^+ h + \frac{M_W^2}{v^2}W^{-,\mu}W_\mu^+ h^2 +$$
$$+\frac{M_Z^2}{v}Z^\mu Z_\mu h + \frac{M_Z^2}{2v^2}Z^\mu Z_\mu h^2.$$

Underground principles of the Standard Model

- $U_Y(1) \times SU_W(2) \times SU_C(3)$ symmetry
- Local gauge invariance
- Masses of SM particles are generated due to Higgs mechanism
- Absence of chiral symmetry (even in the massless case)
- Absence of right-handed neutrino
- Presence of quarks and leptons

Structure of the SM

Gauge $U_Y(1) \times SU_W(2) \times SU_C(3)$ invariance requires existance of $SU_W(2)$ left dublets and right singlets. We have $SU_C(3)$ triplets also. Formally, we can have any such dublets (generation) in theory.

$$L_1 = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L ; L_2 = \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L ; L_3 = \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L ; \quad L_4 = \ldots$$

$$E_1 = e_R; E_2 = \mu_R; E_3 = \tau_R; \ E_4 = \ldots$$

$$Q_1 = \begin{pmatrix} u \\ d \end{pmatrix}_L ; Q_2 = \begin{pmatrix} c \\ s \end{pmatrix}_L ; Q_3 = \begin{pmatrix} t \\ b \end{pmatrix}_L ; \quad Q_4 = \ldots$$

$$U_1 = u_R; U_2 = c_R; U_3 = t_R; \ U_4 = \ldots$$

$$D_1 = d_R; D_2 = s_R; D_3 = b_R; \ D_4 = \ldots$$

$$q = \begin{pmatrix} q_r \\ q_g \\ q_b \end{pmatrix}$$

Structure of the SM

Lagrangian of the Standard Model in the gauge invariant form.

$$\mathcal{L}_{SM} = -\frac{1}{4}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4}\sum_{i=1}^{3} V^i_{\mu\nu}V^{i,\mu\nu} - \frac{1}{4}\sum_{a=1}^{8} G^a_{\mu\nu}G^{a,\mu\nu} +$$

$$+ i\bar{L}_n\gamma^\mu\mathcal{D}_\mu L_n + i\bar{E}_n\gamma^\mu\mathcal{D}_\mu E_n + i\bar{Q}_n\gamma^\mu\mathcal{D}_\mu Q_n + i\bar{U}_n\gamma^\mu\mathcal{D}_\mu U_n + i\bar{D}_n\gamma^\mu\mathcal{D}_\mu D_n +$$

$$+ \mathcal{D}_\mu H^+ \mathcal{D}^\mu H - \lambda\left(H^+H - \frac{\nu^2}{2}\right)^2 -$$

$$-\left(Y^l_{mn}\bar{L}_m H E_n + Y^d_{mn}\bar{Q}_m H D_n + Y^u_{mn}\bar{Q}_m\tilde{H}U_n + h.c.\right)$$

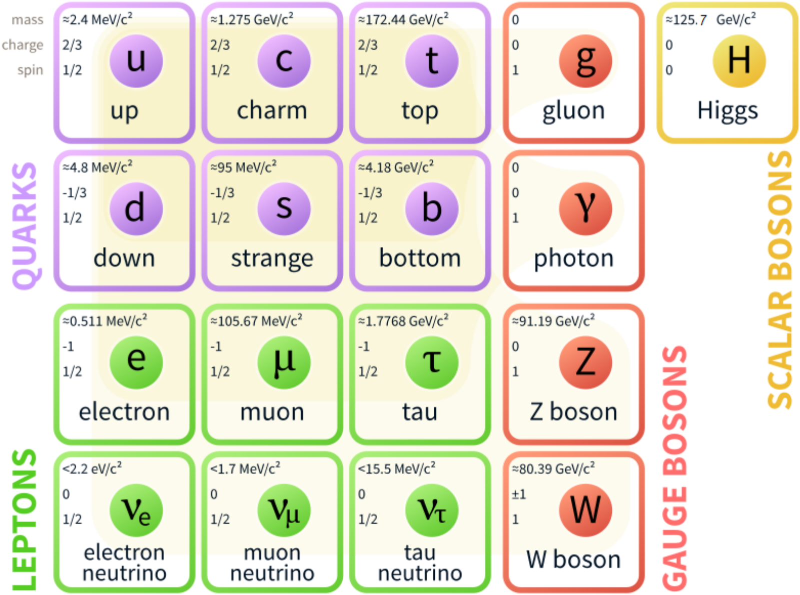
Who and when created this theory?



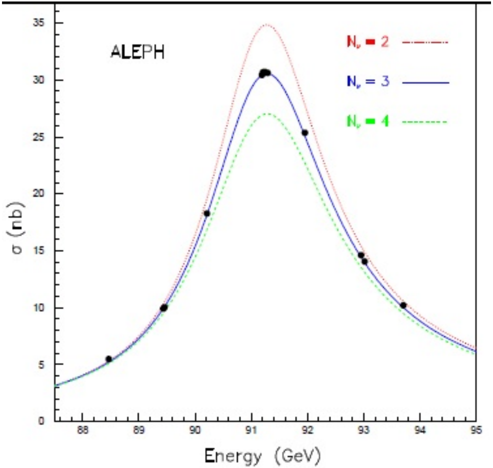
The first step towards the Standard Model was Sheldon Glashow's discovery in 1961 of a way to combine the electromagnetic and weak interactions. In 1967 Steven Weinberg and Abdus Salam incorporated the Higgs mechanism into Glashow's electroweak interaction, giving it its modern form.

https://en.wikipedia.org/wiki/Standard_Model

Particles filling of the SM



Number of generations



The $e^- e^+ \to hadron$ cross section as a function of center-of-mass energy, as measured by *ALEPH*. The curves represent the Standard Model predictions for two, three and four species of light neutrinos. It is clear from this picture that there is no further light neutrino species with couplings identical to the first three.

Standard Model success

The neutral weak currents caused by Z boson exchange were discovered in 1973. The $W^{\pm}$ and Z bosons were discovered experimentally in 1983; and the ratio of their masses was found to be as the SM predicted. **It was solved the problem of renormalizability of the Fermi theory!**

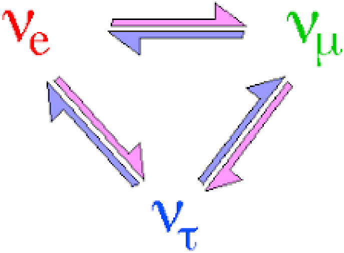
Before creating of SM it were known only three quarks: u, d, s! In 1974 was discovered second quark of second generation c. In 1977 was discovered first quark of third generation (**it's necessary for explaining CP-violation**) – b-quark. In 1995 second quark of third generation (t-quark) was discovered.

In 2012 Higgs boson was experimentally discovered. It gives masses for all particles and allows to introduce masses in $W^{\pm}$ and Z bosons in gauge invariant theory due to spontaneously breaking symmetry $SU_W(2) \times U_Y(1) \to U_{EM}(1)$.

Problems of SM

1. Neutrino oscillation

Neutrino oscillation is a quantum mechanical phenomenon whereby a neutrino created with a specific lepton family number ("lepton flavor": electron, muon, or tau) can later be measured to have a different lepton family number.
First predicted by *Bruno Pontecorvo* in 1957. The first experimental evidence for neutrino oscillations (atmospheric) was announced in 1998.



Problems of SM

1. Neutrino oscillation

Observation of oscillation says: neutrino are **massive** particles $\sum m_\nu < 0.17$ eV.
Flavor state of neutrino and mass state of neutrino are different states !!!

The SM was constructed under assumption that **neutrino are massless** ! The problem is in that

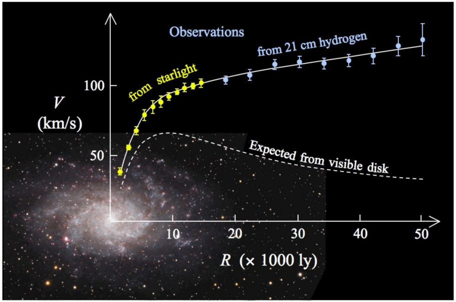
$$\mathcal{L}_m = -m\bar{\psi}\psi = -m(\bar{\psi}_L\psi_R + \bar{\psi}_R\psi_L).$$

we need right-handed neutrinos, **that are not observed**.
Alternatively, we need neutrinos of Majorana type (true neutral particles, right-handed state is just charge conjugated left-handed state) !!! But all other particles in SM are particles of Dirac type.

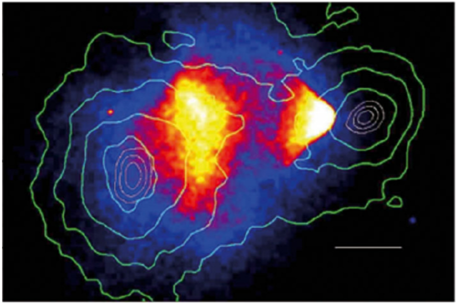
Problems of SM

2. Dark matter

The first to suggest the existence of dark matter, using stellar velocities, was Dutch astronomer Jacobus Kapteyn in 1922. Fellow Dutchman and radio astronomy pioneer Jan Oort also hypothesized the existence of dark matter in 1932.



Galaxy rotation curve



Bullet Cluster, 1E 0657-558

Problems of SM

3. Dark energy

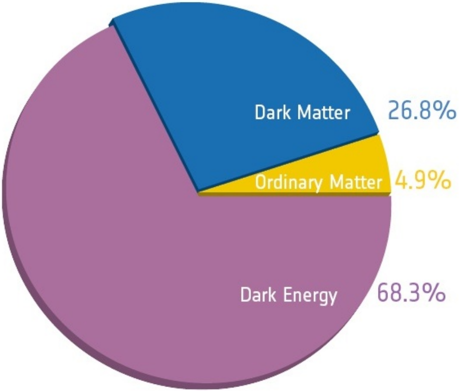
Dark energy is an unknown form of energy which is hypothesized to permeate all of space, tending to accelerate the expansion of the universe. Dark energy is the most accepted hypothesis to explain the observations since the 1990s indicating that the universe is expanding at an accelerating rate.

For dimensional reasons, the value of the vacuum energy density should be $\sim M^4$, where M is the characteristic energy scale (mass of the interaction carrier) of a certain interaction. For strong interaction $M \sim 1$ GeV and $\rho_{vac} \sim 1$ GeV^4, for weak interaction $M \sim 100$ GeV and $\rho_{vac} \sim 10^4$ GeV ^{4}, for a gravitational – $M \sim M_P \sim 10^{19}$ GeV and $\rho_{vac} \sim 10^{76}$ GeV ^{4}.
However, the value of density of the dark energy is only $\rho_{DE} \sim 10^{-46}\mathrm{GeV}^4$ ($\rho_{DE} \simeq 6.47 \cdot 10^{-27}\mathrm{kg/m}^3$), that is very small !!! $\rho_{DE}^{1/4} \sim M = 10^{-3}$ eV !!!
What is it?

Problems of SM

Unknown known Universe

In all observable Universe we know only 5% of its composition.



Should we believe that new particles exist? Physics **Beyond** the Standard Model

Neutrino masses and oscillations

What makes neutrinos disappear and then re-appear in a different form? Why do they have mass?

- Neutrino oscillations do not tell us what is the scale of new physics
- It can be **anywhere** between sub-eV and 10^{15} GeV

Baryon asymmetry of the Universe

what had created tiny matter-antimatter disbalance in the early Universe?

- Physics on the very different scales can be responsible for it

Dark matter

What is the most prevalent kind of matter in our Universe?

- Physics at high scales (10^{12} GeV for axion-like particles), at intermediate scales (TeVs for WIMPs) or at low scales (keV-ish sterile neutrino, physics below electroweak scale) can be responsible for this

Questions about the evolution of the Universe as a whole

Cosmological inflation:

What sets the initial conditions for all the structure that we see in the Universe? (possibly Higgs field)

Dark Energy:

What drives the accelerated expansion of the universe now (possibly this is just Λ-term)

Deep theoretical questions

- Strong CP problem
- Why Planck scale 10^{19} GeV is much higher than the electroweak scale (100 GeV)?
- How to describe gravity quantum mechanically?