Problems in the Standard Model: from neutrino mass to dark matter

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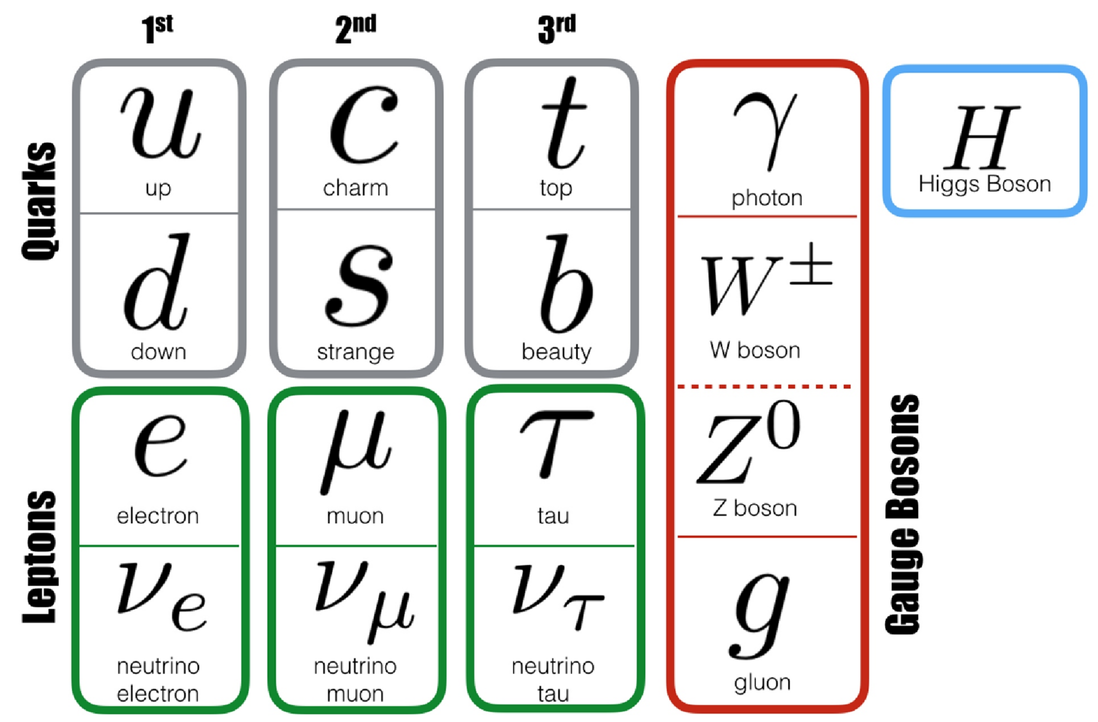
The Standard model and its problems

The Standard Model (SM) agrees with all experimental data, but is theoretically unsatisfactory. It provides a simple theoretical idea how the weak bosons acquire masses, originating from condensation of quanta of Higgs boson. The observed Higgs mass is consistent with the mechanism predicted by SM and with the prediction in supersymmetric SM with relatively large SUSY breaking at 10-100 TeV. Despite its great predictive power and major successes, SM fails answering several questions and incorporate gravity in a consistent theory.

Unsolved problems in the Standard Model:

- vacuum instability problem
- gauge coupling unification
- neutrino mass
- the strong CP problem
- the hierarchy problem
- the flavor problem
- dark matter
- baryon asymmetry
- L and B number violations
- cosmological constant problem
- quantum triviality and Landau pole problem
- unification with gravity



SM does not have an answer to any of these problems. A more fundamental physics at a higher energy scale must be predicted, leading to the unanswered characteristics of the Standard Model. All parameters and quantum numbers from the Standard Model should then be derived from a more fundamental description of nature, leading to the Standard Model as an effective low-energy theory. Solutions to the problems should be part of a **Theory of Everything**, that includes gravity, reconciles it with quantum mechanics and explains the origin of space-time and its dimensions.

There are 3 types of problems:

1. **Mass**: origin of particle mass, is it due to a Higgs boson, and, why are the masses so small
2. **Unification**: is there a Grand Unified Theory (GUT) for unifying all the particle interactions?
3. **Flavour**: why so many types of quarks and leptons and how their weak interactions mix?

Unification with Gravity: SM is inconsistent with General Relativity (either one or both of the theories break down under certain conditions), therefore gravity remains unexplained.

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The hierarchy problem: the huge hierarchy between Planck mass and Higgs mass parameter. Solutions: low-energy supersymmetry, composite Higgs models and extra dimensions.

The vacuum instability problem: If there is no new physics between electroweak and Planck scale, there is no stable vacuum. Measurements of Higgs boson and top quark masses indicate that there should be a "true" vacuum with less energy than the present one.

Gauge coupling unification: The renormalization group flow of the coupling constants of the 3 gauge forces intersect at high energy. GUT or supersymmetry theories could explain in which the gauge coupling constants unify exactly at high energy.

Neutrino mass: SM predicts that neutrinos should not have mass but experiments such measuring solar neutrinos have shown neutrinos behave as if they have mass eigenstates between which they can oscillate.

Strong CP problem: QCD preserves CP-symmetry and a violation of CP-symmetry in strong interactions could occur. However, no violation of the CP-symmetry has ever been seen involving only the strong interaction. Solution: the Axion.

The flavor problem: The scale of flavor changing neutral current effects in SU(2)×U(1) breaking theories is 300 GeV. To be larger requires an unnatural fine tuning of the parameters.

Dark matter: SM explains about 5% of the energy present in the universe. About 26% should be dark matter, but which only interacts weakly (if at all) with SM fields.

Baryon assymetry: or the matter-antimatter asymmetry, is the observed imbalance in baryonic and antibaryonic matter in the observable universe.

Lepton and Baryon number violation: B and L are symmetries but the chiral nature of weak interaction produces global anomalies with vanishing B-L but non-vanishing axial current for B+L.

Cosmological constant problem: or vacuum catastrophe is the disagreement between the observed values of vacuum energy density and theoretical large value of zero-point energy from quantum field theory.

Quantum triviality: QED loses its validity at high energies because of the presence of Landau poles. For QCD, the coupling vanishes at high energies, and the "pole" is at low energies. Classical theory describing interacting particles can become a "trivial" theory of non-interacting free particles.

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