Beyond the Standard Model with Low-energy Effective field theories

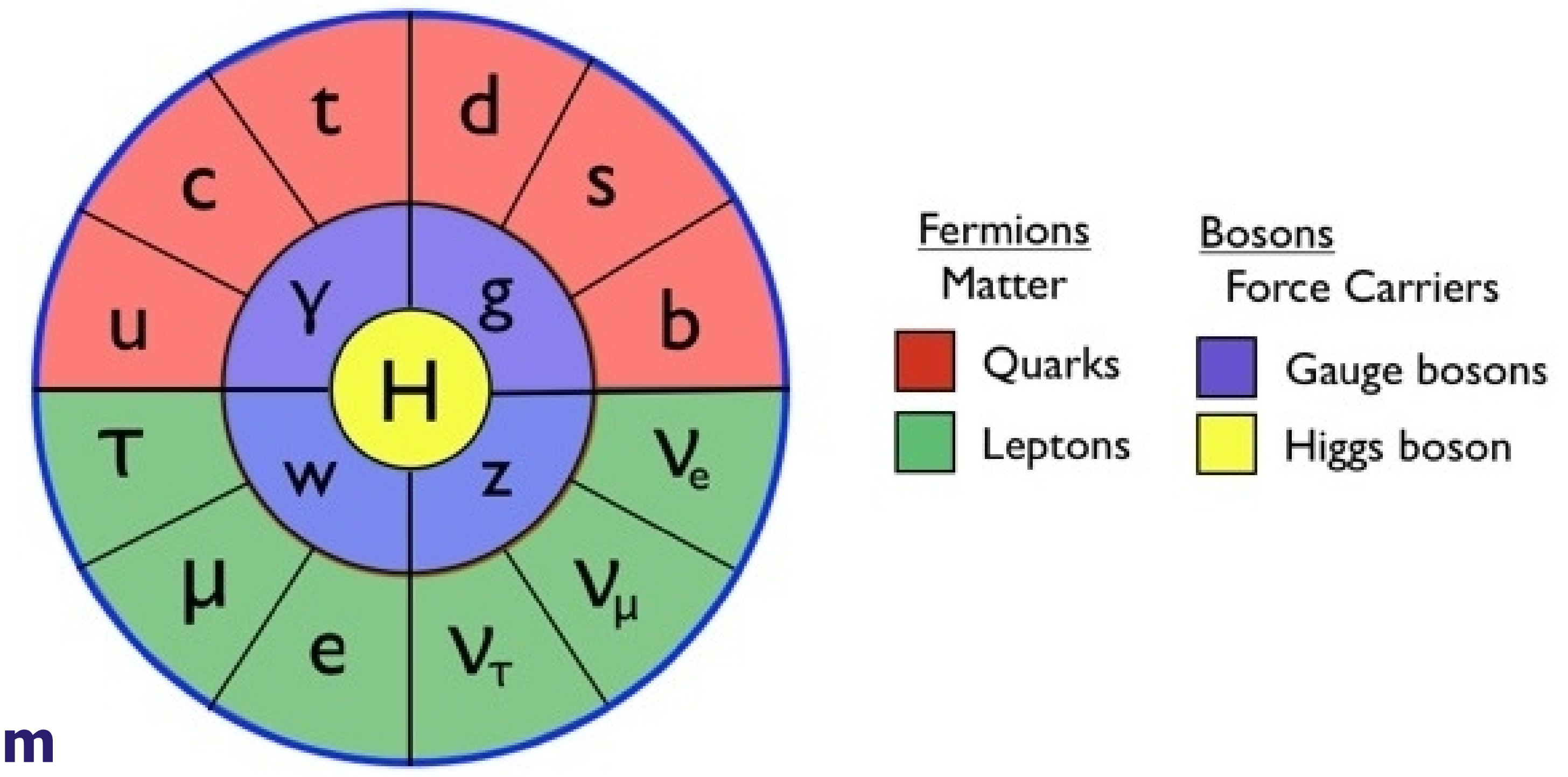
Eric Howard
Department of Physics and Astronomy, Macquarie university
Centre for Quantum Dynamics, Griffith University

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.

Standard Model challenges:

- 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.

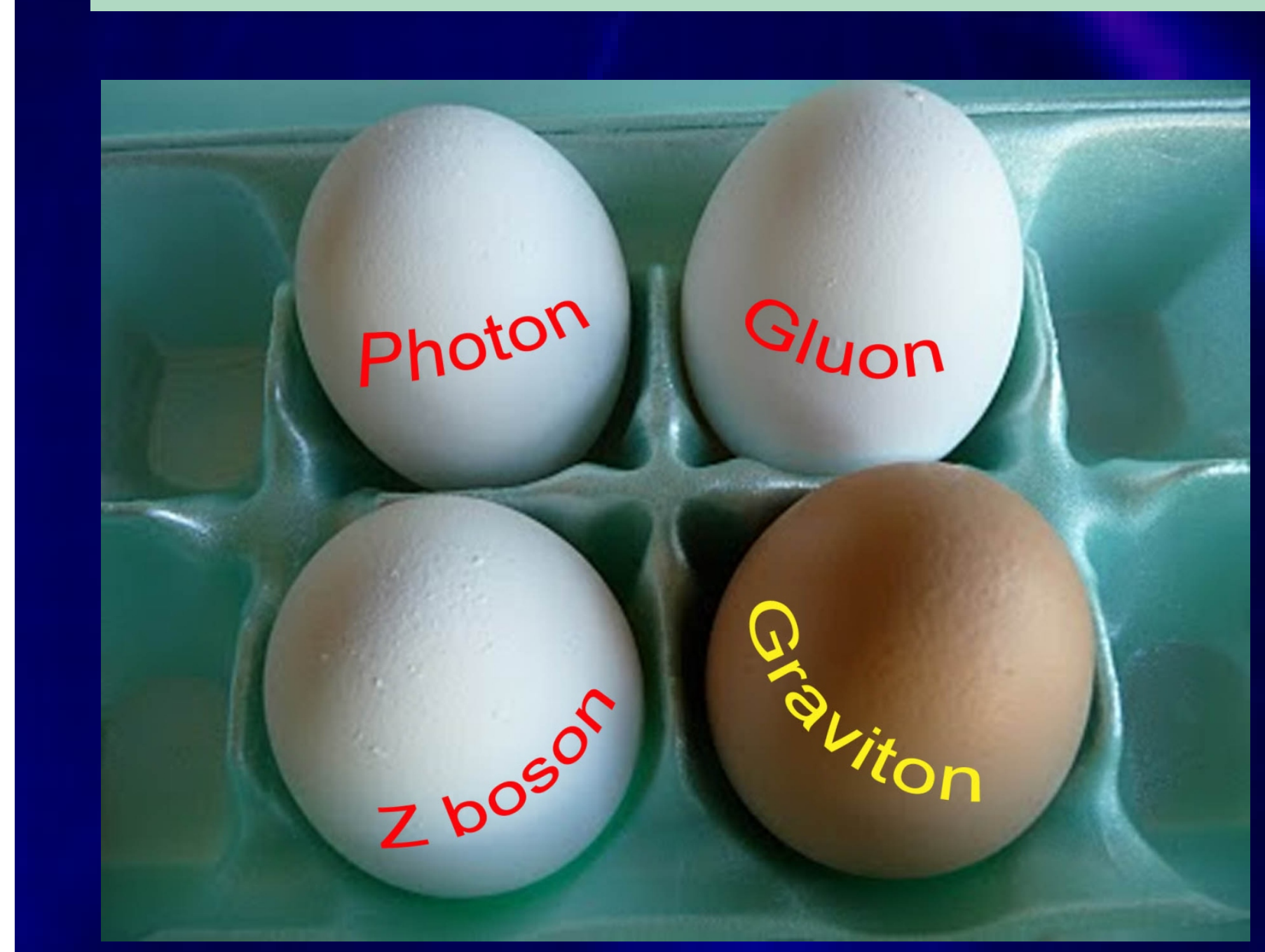
General relativity provides the low energy interactions of the gravitons. At low energies, the quantum degrees of freedom have detectable effects. In a quantum field theory there are significant divergences from high energies in the UV limit. These are not good predictions of gravitons, as general relativity might not be the correct high energy theory. Effective field theory techniques, can separate the unreliable high energy models from the low energy ones. There can be meaningful predictions at low energy.

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.

Low ebergy effective field theories

Despite the great predictive power and recent successes of the Standard Model, strong theoretical and observational reasons lead to a larger picture that should explain the nature of fundamental interactions, including gravity. Low-energy tests of fundamental symmetries and interactions as well as studies of particle properties provide a powerful window on the physics beyond the Standard Model. An Effective Field Theory is a theory that emloys only the active degrees of freedom available at some energy. When a quantum field theory treatment is applied, the findings should contain the quantum corrections appropriate to that energy.

A perturbative model of quantum General Relativity can be seen as an effective field theory, and its quantum corrections can be found. We discuss the current theoretical shortcomings and limitations of the Standard Model, that significantly impact the search for new physics at the frontier of precision physics. As the model fails answering important fundamental questions, such as including gravity in a consistent theory, a low-energy effective theory approach that allows for a general parameterization of Standard Model physics is needed.



A fundamental theory whose effective description at low energies is given by the non-renormalizable Einstein-Hilbert action may be tested, in principle, by low-energy precision methods providing signatures and indirect probes of new physics, complementary to direct searches. Such a new picture should solve existing puzzles, such as the low-energy limit of QCD, the existence of the axion or the hierarchy problem between the electroweak symmetry breaking scaleand the Planck mass scale.

We analyze existing theoretical predictions that go beyond the Standard Model and discuss potential precision tests of fundamental symmetries and their couplings togravity, where low-energy observables play an important role. While the quantum treatment of gravitation presents several theoretical challenges, at low energies and metric curvatures, these problems can be ignored and the effective quantum gravitational field-theory exists as a perturbation to the classical solutions.

However, there has yet to be an experimental test confirming the need for a quantum treatment of gravity. While the quantum gravity signatures are expected to be very small, it was recently shown that they should be observable with the improvement in current experimental techniques, such as cold atom intereferometry or optically levitated nanoparticle sensors. Future indirect constraints from the Standard Model deviations may explain the non-renormalizability of quantum gravity via precision tests of general relativity and its Newtonian limit at short distances.

References:

J. R. Ellis, Lectures at 1998 CERN Summer School, St. Andrews,Beyond the Standard Model forHillwalkers, arXiv:hep-ph/9812235.
J. R. Ellis, J. Hisano, S. Lola and M. Raidal, Nucl. Phys. B621, 208 (2002), arXiv:hep-ph/0109125.
J. R. Ellis, G. Ganis, D. V. Nanopoulos and K. A. Olive, Phys. Lett. B502(2001), 171 arXiv:hep-ph/0009355.
N. A. Bahcall, J. P. Ostriker, S. Perlmutter and P. J. Steinhardt, Science284(1999) 1481, arXiv:astro-ph/9906463.
C. Boehm, A. Djouadi and M. Drees, Phys. Rev. D62(2000) 035012, arXiv:hep-ph/991149].
F. E. Paige, hep-ph/021101.