Particle physics: the flavour frontiers

Lecture 1: Introduction – lagrangians and symmetries

Prof. Radoslav Marchevski

February 19th 2025

Practical information

- Lecturer: Radoslav Marchevski
  web: https://people.epfl.ch/radoslav.marchevski
  mail: radoslav.marchevski@epfl.ch
- Teaching assistant: Luis Miguel Garcia Martin
  web: https://people.epfl.ch/luis.garciamartin?lang=en
  mail: luis.garciamartin@epfl.ch
- Course material:
  Moodle: https://moodle.epfl.ch/course/view.php?id=18370
  will contain slides, exercises, and solutions
  books: Yuval Grossman and Yosef Nir: “The Standard Model: from fundamental symmetries to experimental tests” (library)
  “Just a Taste” – Lectures on flavour physics by Yuval Grossman and Philip Tanedo (available on arXiv, arXiv:1711.03624)
  Particle Data Group “The Review of Particle Physics” https://pdg.lbl.gov/
  Introduction to QFT: SM and Flavor - Yuval Grossman (ICTP school, recorded on YouTube)

Provide regular feedback

General

Collapse all

Organisation and timing

Each week, there will be the following materials and activities:

- Live lecture with slides shared via moodle. We currently don't plan to record the lectures.
- Exercise class with several exercises to solve and to go through with the help of a TA.

Course teachers

- Lecturer: Prof. Radoslav Marchevski
- Teaching assistant: Luis Miguel Garcia Martin

Course time and location

- Lecture sessions: Wednesdays 10:15 - 12:00 in BS 270
- Exercise sessions: Wednesdays 13:15 - 15:00 in BS 270

Reading list

The main book on the Standard Model is the book by Yuval Grossman and Yosef Nir: "The Standard Model: from fundamental symmetries to experimental tests" that can be found in the library, as well as the "Just a Taste" lecture series available on arXiv (arXiv:1711.03624).
For summaries, most recent reviews and technical information, please use the Particle Data Group (PDG) website https://pdg.lbl.gov/.

Announcements

Forum for Q&A on the lectures and exercises

February 21 - Lecture 1: Introduction - lagrangians and symmetries This week

Grossman and Nir: Chapter 1

- For each lecture & exercise session, you can share your feedback via moodle.
- Do not hesitate to talk to us after the lecture/exercise session or send us an email.

Today's learning targets

<u>After today you should be able to answer the following questions</u>

- What is flavour?
- What patterns do we see when we look at probabilities for different flavour processes in data?
- What are the main goals of particle (high-energy) physics?
- What ingredient do we need to construct the complete Lagrangians of Nature?

Introduction

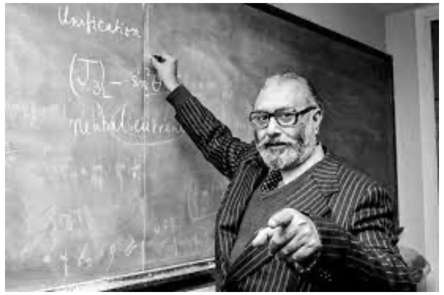
- Main goal of particle physics (also known as high energy physics):

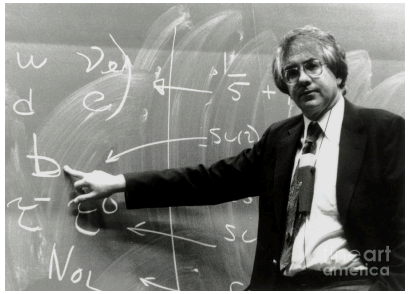
Understand what are the fundamental laws of Nature

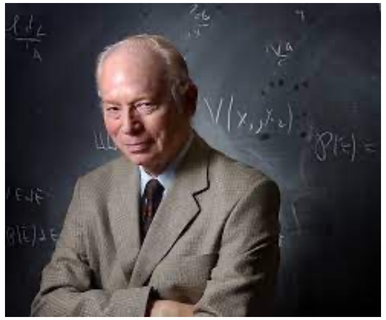
- Particle physics experiments probed energy scales as high as 10 TeV ($m_p \sim 1$ GeV) $\leftrightarrow$ distances $10^{-20} m$
- We understanding of how Nature works at such short distances: amazing achievement!
- The framework to describe phenomena at such small distances is called *Quantum Field Theory (QFT)*
  - Different from Classical and Quantum Mechanics
  - Surprisingly similar underlying principles of physics: principle of minimal action and symmetry arguments

Introduction

- Currently accepted theory of particle physics is called the **Standard Model (SM)**
- Conceived in the late 60s and early 70s by Glashow, Weinberg and Salam





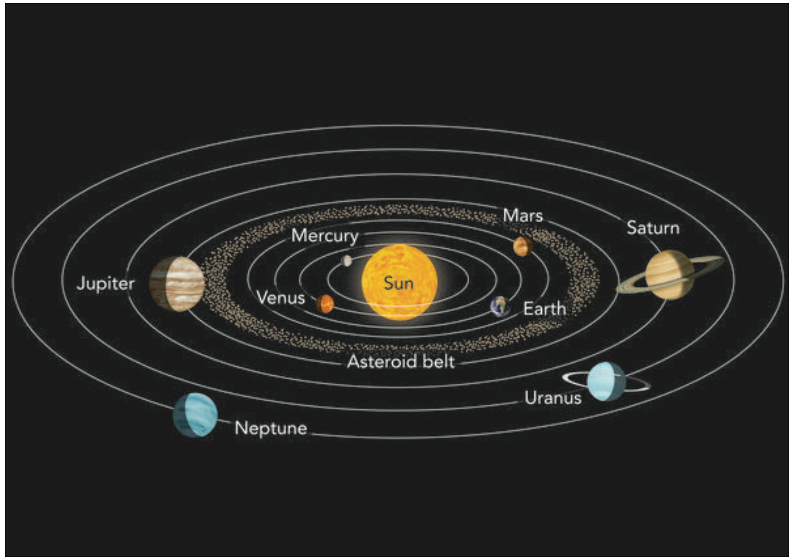


- Many of the particles that are now part of the SM were not yet discovered at that time
- By 2012 the full list of SM particles had been directly produced and detected
- SM tested by numerous experimental measurements, and passed almost all tests with flying colours
- Very few failures $\Longrightarrow$ starting points for the road to an even deeper understanding of Nature

Introduction

- Significant breakthroughs in physics are often achieved when realizing that phenomena that appear to be different are actually connected!

Planets' motion around the Sun



Explained by the same law of gravity

Apples falling from a tree

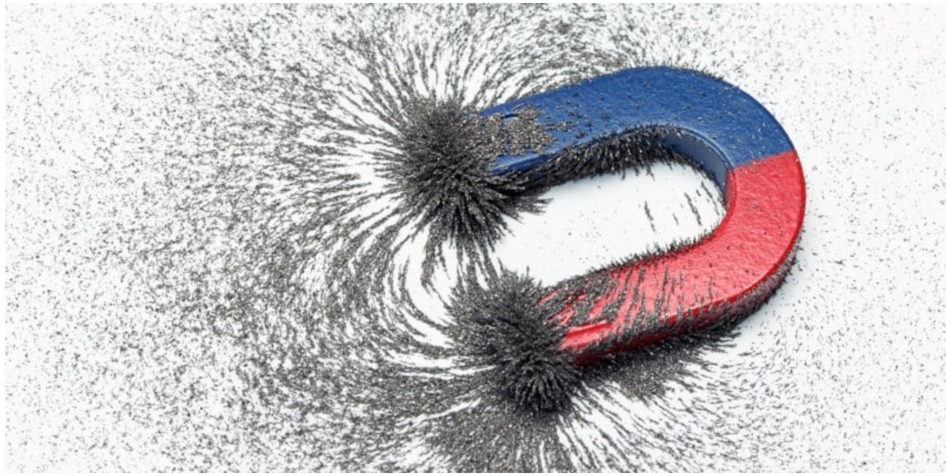
Introduction

- Significant breakthroughs in physics are often achieved when realizing that phenomena that appear to be different are actually connected!

Electricity

Manifestation of the unified electromagnetic theory

Magnetism



Introduction

- Significant breakthroughs in physics are often achieved when realizing that phenomena that appear to be different are actually connected: particle physics is not an exception
- We typically say that there are four forces: strong, weak, electromagnetic, gravitational
- The SM includes the description of three out of the four forces (except gravity)
- The three forces appear very different from each other (*only at first glance*)
    - At the fundamental level they all arise from a QFT incorporating gauge symmetries (locality)
    - We can think of it as a generalization of Quantum Electrodynamics (QED)
    - The unification of the underlying principle – gauge symmetries – makes for an elegant theory

How to find the basic laws of nature

- The basic laws of nature are encoded in the action S

$$S = \int d^4x \, \mathcal{L}$$

- $d^4x = dx^0 dx^1 dx^2 dx^3$ – integration measure in four-dimensional Minkowski space
- $\mathcal{L}$ – "Lagrangian density" or Lagrangian
- The QFT equivalent of the generalized coordinates of classical mechanics are the fields
- **Our main task is to find the complete Lagrangian of nature**

$$\mathcal{L} = ?$$

Properties of the Lagrangian

$$\mathcal{L}\left[\phi_i(x), \partial_\mu \phi_i(x)\right] = ?$$

1. It is a function of the fields and their derivatives only (we denote a generic field with ϕ_i)
2. It depends on the fields taken at one spacetime point x^μ only, leading to a **local field theory**
3. It is real, so that the total probability is conserved
4. It is invariant under the Poincare group (spacetime translations and Lorentz transformations)
5. It is an analytic function in the fields (not a general requirement but common to all field theories solved via perturbation theory)

Properties of the Lagrangian

$$\mathcal{L}\left[\phi_i(x), \partial_\mu \phi_i(x)\right] = ?$$

6. It is invariant under certain internal symmetry groups reflecting basic symmetries of the physical system and leading to conserved quantities

7. Democratic principle: every term in the Lagrangian that is not forbidden by any symmetry should appear

8. Renormalizability: a renormalizable Lagrangian contains only terms that are of dimension less than or equal to four in the fields and their derivatives

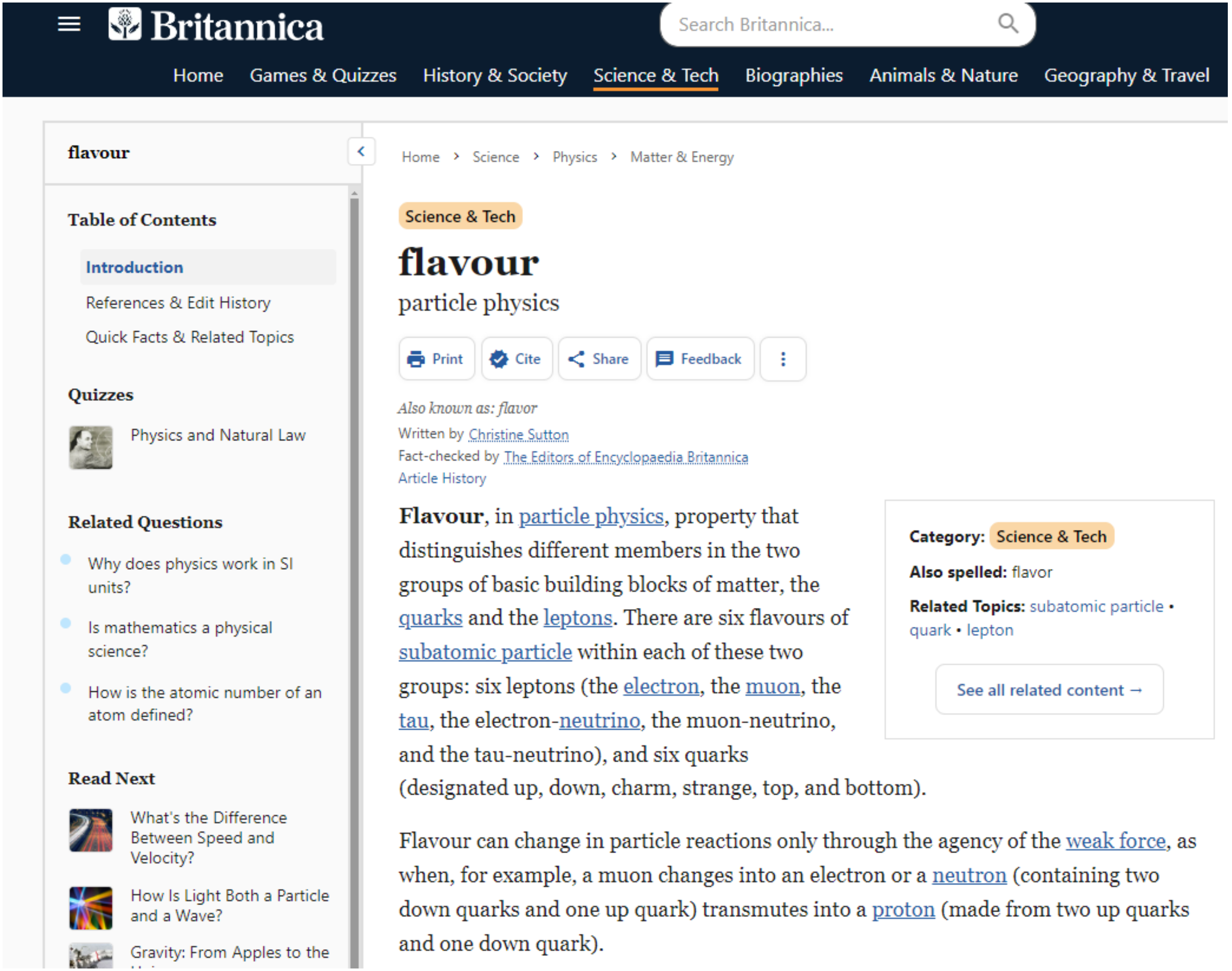
Renormalization

- The SM is believed not to be the complete theory of Nature
- The SM is a low-energy Effective Field Theory (EFT) valid up to an energy scale $\Lambda_{\rm NP}$
  - In the full theory of nature described by a QFT, its Lagrangian must be renormalizable
  - In the SM, for energies approaching Λ_{NP} we must include also non-renormalizable terms $1/\Lambda_{NP}^{n}$, $n = 1, 2, \ldots$
  - For most purposes, the renormalizable terms constitute only the leading term in an expansion in $E/\Lambda_{\rm NP}$ ($E -$ energy scale of the process under study)
  - Higher orders are very suppressed, especially if $E/\Lambda_{\rm NP} \ll 1$
- EFTs work best if there is a large separation between the length scale of interest and the length scale of the underlying dynamics

Renormalization

- EFT includes the appropriate degrees of freedom (DoF) to describe physical phenomena occurring at a chosen length (energy) scale, while ignoring substructure and DoF at shorter distances (high energies)
- Renormalization specifies the relationship between parameters in the theory when parameters describing long distance (low energy) scales differ from parameters describing short distance (high energy) scales
- Renormalization is simply the procedure of systematically moving between scales!

What is flavour?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flavour

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- Physics and Natural Law

Related Questions
- Why does physics work in SI units?
- Is mathematics a physical science?
- How is the atomic number of an atom defined?

Read Next
- What's the Difference Between Speed and Velocity?
- How Is Light Both a Particle and a Wave?
- Gravity: From Apples to the

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Science & Tech

flavour

particle physics

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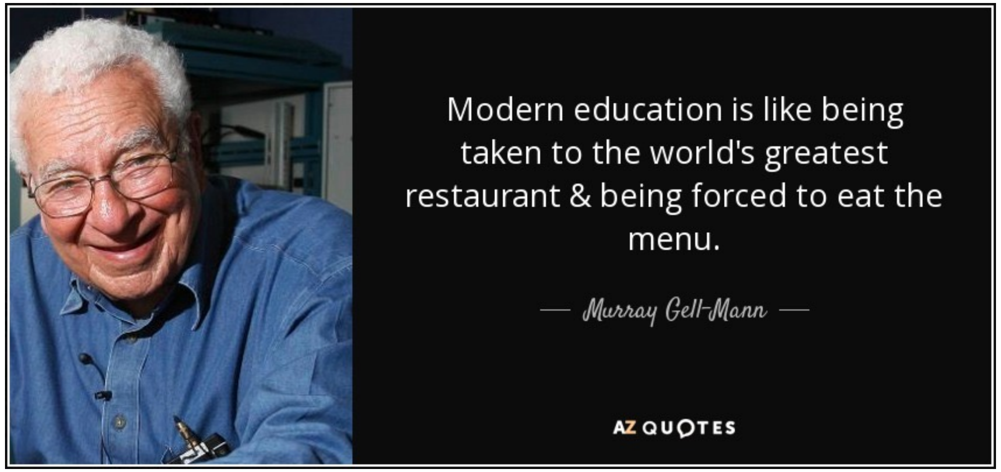
Also known as: flavor
Written by Christine Sutton
Fact-checked by The Editors of Encyclopaedia Britannica
Article History

Flavour, in particle physics, property that distinguishes different members in the two groups of basic building blocks of matter, the quarks and the leptons. There are six flavours of subatomic particle within each of these two groups: six leptons (the electron, the muon, the tau, the electron-neutrino, the muon-neutrino, and the tau-neutrino), and six quarks (designated up, down, charm, strange, top, and bottom).

Category: Science & Tech
Also spelled: flavor
Related Topics: subatomic particle • quark • lepton
See all related content →

Flavour can change in particle reactions only through the agency of the weak force, as when, for example, a muon changes into an electron or a neutron (containing two down quarks and one up quark) transmutes into a proton (made from two up quarks and one down quark).

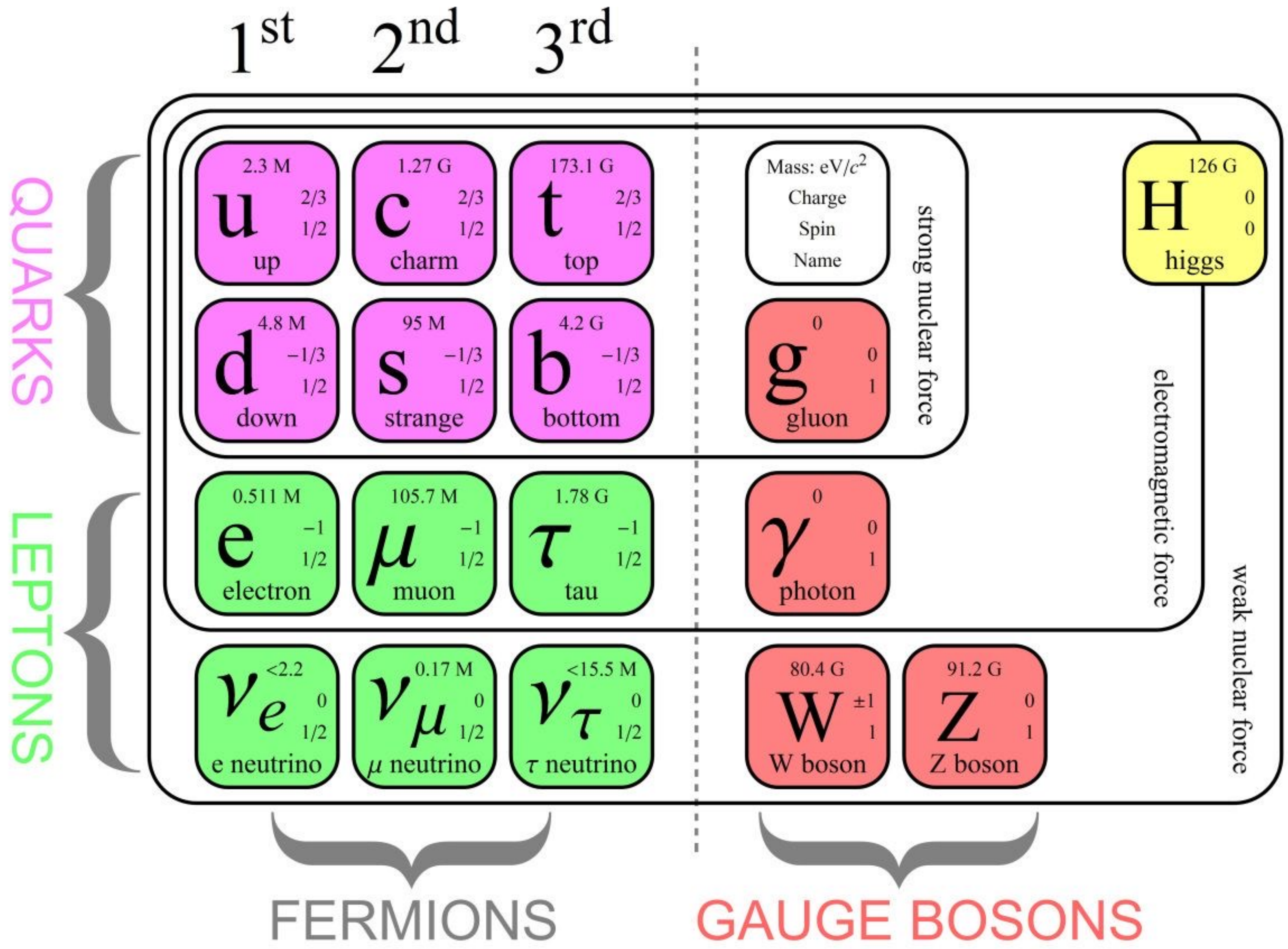


Inspirational quote

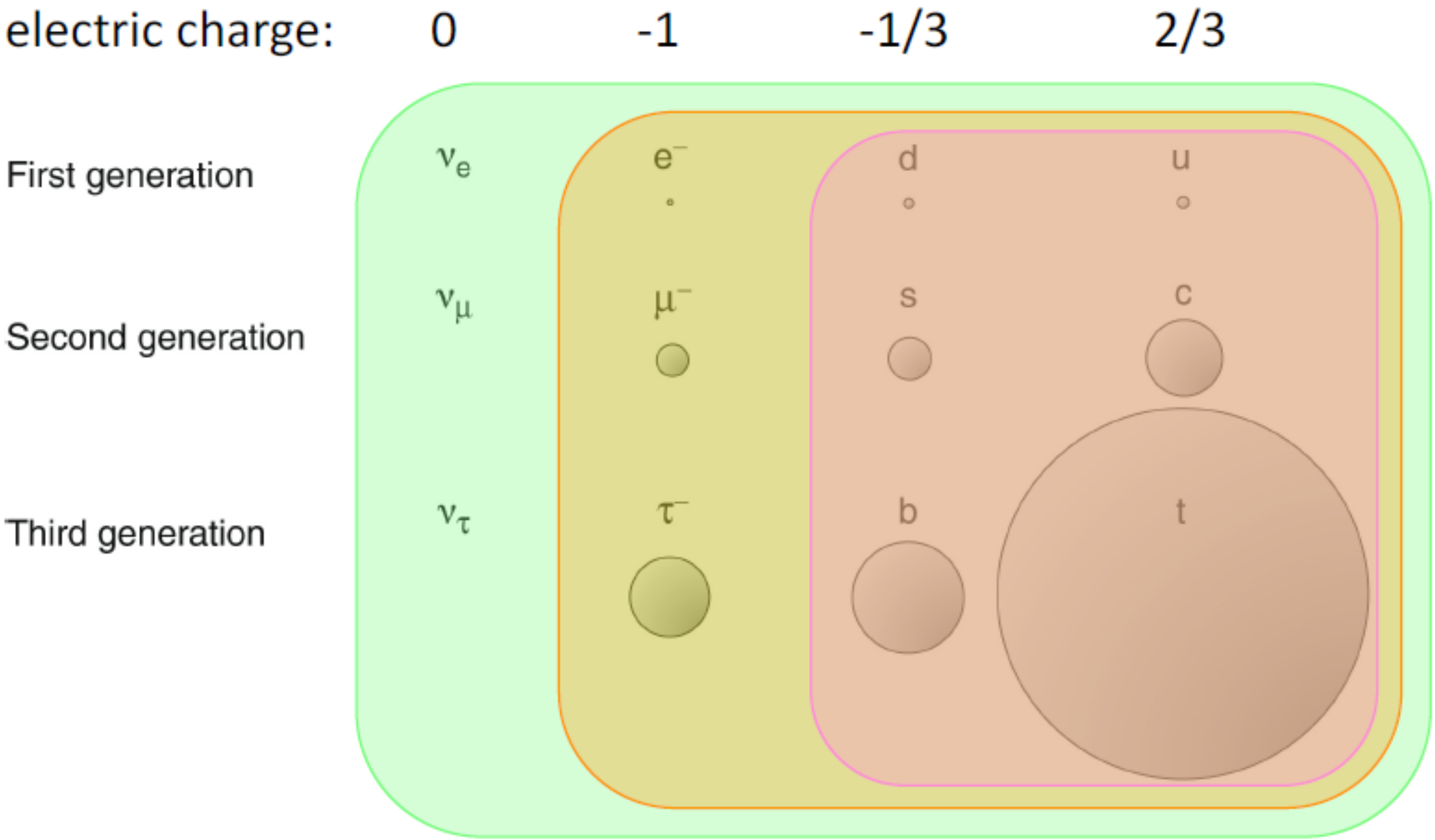
"The term flavor was first used in particle physics in the context of the quark model of hadrons. It was coined in 1971 by Murray Gell-Mann and his student at the time, Harald Fritzsch, at a Baskin-Robbins icecream store in Pasadena. Just as ice cream has both color and flavor so do quarks."

RMP 81 (2009) 1887

The Standard Model (SM) for pedestrians



The Standard Model (SM) for pedestrians



H: Higgs

$W^\pm$, Z: weak

γ: electromagnetic

g: strong

A "random" selection of measured processes from the PDG

- $\mathcal{B}(D^+ \to \bar{K}^0 e^+ \nu_e)[c \to s e^+ \nu_e] = 8.72(9) \times 10^{-2}$
- $\mathcal{B}(D^+ \to \bar{K}^0 \mu^+ \nu_e)[c \to s \mu^+ \nu_\mu] = 8.76(19) \times 10^{-2}$
- $\mathcal{B}(B^- \to D^0 \mu^- \bar{\nu}_\mu)[b \to c \mu^- \bar{\nu}_\mu] = 2.3(1) \times 10^{-2}$
- $\mathcal{B}(B \to X_s \gamma) \quad [b \to s\gamma] = 3.22(15) \times 10^{-4}$
- $\mathcal{B}(B_s \to \mu^+ \mu^-) \quad [b \to s \mu^+ \mu^-] = 3.01(35) \times 10^{-9}$
- $\mathcal{B}(B^- \to \pi^0 \mu^- \bar{\nu}_\mu) \, [b \to u \mu^+ \nu_\mu] = 7.8(3) \times 10^{-5}$
- $\mathcal{B}(K_L \to \mu^+ \mu^-) \quad [s \to d \mu^+ \mu^-] = 6.84(11) \times 10^{-9}$
- $\mathcal{B}(K^+ \to \mu^+ \nu_\mu) \quad [s \to u \mu^+ \nu_\mu] = 63.56(11) \times 10^{-2}$
- Do you see any pattern in the data

What do we learn from the data?

- **Lepton universality –** swapping one generation of leptons with another does not appear to affect the branching ratios of these transitions
- **Flavour-changing neutral currents are small –** on the other hand, processes that change flavour are suppressed for charge-neutral transitions compared to transitions between hadrons of different charge
- **Generation hierarchy –** decays between third and first generation are suppressed compared to that of third to second generation
- *Hopefully by the end of this course you will know why these patterns emerge, how they were discovered experimentally and what more can we learn by studying flavour processes*

Important message

(Almost) all experimental data for elementary particles and their interactions can be explained by the standard model of a spontaneously broken $SU(3)\times SU(2)\times U(1)$ gauge symmetry *

* The main hope of the high-energy physics community is to prove this statement wrong and find an even more fundamental theory

How to build simple Lagrangians? *Scalar fields*

- We call them simple because we haven't imposed any internal symmetries yet
- We use $\phi(x)$ for a scalar, $\psi(x)$ for a fermion field, and $A(x)$ for a vector field (x –spacetime coordinates)
  - We use ϕ, ψ, A as notation and the spacetime dependence is implicit
- Most general renormalizable Lagrangian for a single real scalar field ϕ is given by

$$\mathcal{L}_S = \underbrace{\frac{1}{2}\left(\partial_\mu \phi\right)(\partial^\mu \phi)}_{\text{Kinetic term}} \; \underbrace{- \frac{m^2}{2}\phi^2}_{\text{Mass term}} \; \underbrace{- \frac{\eta}{2\sqrt{2}}\phi^3 - \frac{\lambda}{4}\phi^4}_{\text{Interaction terms}}$$

Kinetic term (important if we want ϕ to be a dynamic field)

Mass term

Interaction terms

- Terms with five or more scalar fields ($\phi^n, n \geq 5$) are non-renormalizable

How to build simple Lagrangians? *Fermion fields*

- Basic fermion fields are two-component Weyl spinors ψ_L and ψ_R
  - L stands for left-handed and R for right-handed chirality
  - Each ψ_L and ψ_R has two degrees of freedom and is a complex field
- The Weyl spinors are related to the Dirac field ψ by

$$\psi_R = P_R\psi = \frac{1+\gamma_5}{2}\psi, \qquad \psi_L = P_L\psi = \frac{1-\gamma_5}{2}\psi$$

- Define the charge conjugation operation C

$$\psi_R^c = C\overline{\psi_R}^T, \qquad \psi_L^c = C\overline{\psi_L}^T$$

How to build simple Lagrangians? *Fermion fields*

- The most general renormalizable Lagrangian for ψ_L and ψ_R

$$\mathcal{L}_F = \underbrace{i\overline{\psi_L}\partial_\mu\gamma^\mu\psi_L + i\overline{\psi_R}\partial_\mu\gamma^\mu\psi_R}_{\text{Kinetic term}} - \underbrace{\left(\frac{m_{MR}}{2}\overline{\psi_R^c}\psi_R + \frac{m_{ML}}{2}\overline{\psi_L^c}\psi_L + m_D\overline{\psi_L}\psi_R + h.c.\right)}_{\text{Mass terms}}$$

Kinetic term
(important if we want $\psi_{L/R}$
to be dynamic fields)

Mass terms – m_M are called Majorana and m_D
are called Dirac mass terms

- Terms with four or more fermion fields are non-renormalizable

- Majorana masses are made of a pair of identical fields we could write $m_{MR}/2\,\overline{\psi_R^c}\psi_R \rightarrow m_{MR}/2\,\psi_R^T\psi_R$

- In case Majorana masses vanish $m_{MR} = m_{ML} = 0$, $\mathcal{L}_F$ can simply be written as

$$\mathcal{L}_F(m_M = 0) = i\bar{\psi}\partial_\mu\gamma^\mu\psi - m_D\bar{\psi}\psi$$

How to build simple Lagrangians? *Fermion + scalar fields*

- The most general renormalizable Lagrangian for ψ_L, ψ_R, and a scalar ϕ

$$-\mathcal{L}_{\text{Yuk}} = \frac{Y}{\sqrt{2}}\phi\overline{\psi_L}\psi_R + \frac{Y_{MR}}{2}\phi\overline{\psi_R^c}\psi_R + \frac{Y_{ML}}{2}\phi\overline{\psi_L^c}\psi_L + h.c.$$

- In addition to $\mathcal{L}_S$ and $\mathcal{L}_F$ that involve only scalar or only fermion fields we can add terms that involve both scalar and fermion fields
- Note the $-$ sign in front of $\mathcal{L}_{\text{Yuk}}$: a common practice if we don't write the kinetic terms
- Y parameters are dimensionless and are called *Yukawa* couplings

Symmetries

Who is this?

- **Symmetry:** invariance of the equations that describe a physical system
- Symmetries are built into our physics models as invariance properties of the Lagrangian
- We encode empirical facts and observed conservation laws in our theories which as a result exhibit certain invariance properties
- Some symmetries are not imposed but are accidental (outputs of the theory rather than external constraints)

Two points of view

Implement observed conservation laws in the theory ⇔ **Resulting symmetry of $\mathcal{L}$**

Take symmetries as fundamental rules ⇔ **Conservation laws resulting from the symmetry principle**

Symmetries

Who is this?

- Two types of symmetries particularly relevant for our discussions

Spacetime symmetries

Internal symmetries

- Can you think of examples of spacetime and internal symmetries?
- What conservation laws do they give rise to?

Symmetries

Who is this?

- Two types of symmetries particularly relevant for our discussions

Spacetime symmetries

- Poincare group (translations, rotation, boosts)
  - give rise to energy-momentum and angular momentum conservation laws
- Discrete space inversion (parity P), time-reversal T, and charge conjugation C

Internal symmetries

- Internal symmetries act on the fields and not directly on spacetime ($SU(3)_c, SU(2)_L, U(1), \dots$)
- They act in internal mathematical spaces generated by the fields
- *Example:* gauge symmetries
  - $U(1)$ global symmetry gives rise to conservation of electric charge

Model designing

- The Lagrangian is the endpoint of model building
- Procedure of constructing Lagrangians
  - we define the set of all symmetries the Lagrangian must obbey
  - we define the transformation properties of the various scalar and fermion fields under the symmetry operation
  - we write the most general Lagrangian the depends on the fields and is invariant under the symmetry
- In this course we will not focus on model building but rather on a mixture of experimental results and phenomenological insights
- Nevertheless, understanding these principles is essential to understanding the SM and its experimental and phenomenological consequences
  - we will use the principles to construct the Standard Model Lagrangian

Summary of Lecture 1

<u>Main learning outcomes</u>

- What is flavour and what patterns do we see by looking at flavour processes in the data
- What is the scope of particle physics and how do we go about constructing the complete Lagrangian of Nature
- Symmetries and their link to conservation laws