Introduction to particle physics
Lecture 3

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Outline

1. Fundamental forces

2. Symmetries
Fundamental forces

The four forces in nature

- **Electromagnetic**
  - Photon
  - Atoms
  - Light
  - Chemistry
  - Electronics

- **Gravitational**
  - Graviton?
  - Solar system
  - Galaxies
  - Black holes

- **Strong**
  - Gluons (8)
  - Quarks
  - Mesons
  - Baryons
  - Nuclei

- **Weak**
  - Bosons (W,Z)
  - Neutron decay
  - Beta radioactivity
  - Neutrino interactions
  - Burning of the sun
How forces act

- **Forces act through exchange particles** associated with them.
Gravity

- Most familiar force, but: Important only in macro-world!
- Newton’s law: \( F = G \frac{Mm}{r^2} \) (\( G = \) Newton’s constant)
  (implicit: Gravitational = inertial mass)
- General relativity: \( G_{\mu\nu} = 8\pi G T_{\mu\nu} \),
  where \( G_{\mu\nu} = \) metric, and \( T_{\mu\nu} = \) energy-momentum tensor.
- Quantum formulation of gravity tricky - seemingly not renormalisable.
- But: Gravity becomes quantum at roughly the Planck mass:
  \[ M_{\text{Planck}} = \sqrt{\frac{\hbar c}{G}} = 1.2209 \cdot 10^{19} \text{ GeV} = 2.17645 \cdot 10^{-8} \text{ kg}. \]
- Carrier of gravity (hypothetical): massless spin-2 graviton
# Electromagnetism

- Force that we understand best - both classically and quantum. (Because the coupling strength \( e, \frac{e^2}{4\pi} = \alpha \approx 1/137 \) small enough for perturbation theory!)
- Coulomb force law for static charges: \( F = K \frac{q_1 q_2}{r^2} \).
- Equations governing the laws of classical electromagnetism:
  - **Maxwell’s laws.**
  - Structure: Two fields (\( \vec{E} \) and \( \vec{B} \) - vector and axial vector), all first derivatives, currents and charges \( \rightarrow \) 4 equations:
    - One scalar, pseudoscalar, vector, axial-vector equation.
- Interesting: the sources are asymmetric (no magnetic monopole!).
- Carrier of electromagnetism: **massless spin-1 photon**
Electromagnetic waves

![Image of electromagnetic spectrum]

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The first quantum field theory: QED

- Quantum ElectroDynamics (QED) describes the interactions of electrically charged particles (electrons, ...) with the electromagnetic field.

- It has only one interaction vertex, namely $ee\gamma$.

- It was the first realistic quantum field theory and served as an example for the construction of all other theories.

- Important feature: Using gauge invariance (see later) as a construction principle to generate interactions.
Detour: How to draw Feynman diagrams

**Rules for QED**
- For simplicity: Fix a time-axis.
- Fermions (electrons and positrons) are represented with straight lines and arrows and photons with wavy lines.
- If the arrow points (anti-)parallel to the time-axis: (anti-)particle. This is relevant only for external particles.
- Along a fermion line, “clashing arrows” are not allowed - they are related to fermion number (charge) violation.

**Examples**
- Bhabha-Scattering
  \((e^- e^+ \rightarrow e^- e^+)\)

- Pair annihilation
  \((e^- e^+ \rightarrow \gamma \gamma)\)
How (not) to draw Feynman diagrams - Counterexamples

**Illegal vertex**
- Rule: Use only vertices that are present in the theory. They exactly correspond to the interaction terms in the Hamiltonian.
- In QED: Only $ee\gamma$ vertex.
- In example: Used an $ee\gamma\gamma$ vertex.

**Clashing arrows**
- Rule: Don’t revert the arrow along a fermion line (flow of quantum numbers and conservation laws).
- In QED: fermion number and electrical charge.
- In example: globally okay, locally (at each vertex) wrong.
Electron’s anomalous magnetic moment in QED

- “Classically”, intrinsic magnetic moment of a particle with charge $q$, mass $m$ and spin $s$ given by:
  
  $$\vec{\mu} = g \frac{q}{2m} \vec{s} \text{ with } g = 2.$$ 

- However, $g$ is altered by quantum corrections, necessitating renormalisation and also giving rise to finite corrections.

- First calculation by Schwinger in 1948 (diagram above), yielding
  
  $$\frac{g - 2}{2} = \frac{\alpha}{2\pi} \approx 0.0011614.$$ 

- By now, one of the most precise number in physics:
  
  $$\left. \frac{g - 2}{2} \right|_{\text{exp}} = 0.00115965218085(76)$$ 

- 10 digits-agreement with theory $\Rightarrow$ used for precise value of $\alpha$. 
Weak nuclear force

- Most obvious “everyday” feature: triggers neutron decay.
- Decay mode: $n \rightarrow pe^- \bar{\nu}_e$, half-life around 10 minutes
  $\implies$ force responsible for the neutron decay must be weak.
- The same force (and typically also the same decay channel) is
  responsible for radioactive $\beta$-decay.
- Neutrinos $\nu$ only interact through the weak force, very hard (near
  impossible) to detect: Needs huge detectors.
- Carriers of weak force: massive spin-1 electroweak gauge bosons
  $W^\pm$ and $Z^0$.
- Large mass of carriers limits range of force.
Aside: Neutrinos

- Hypothesised by Pauli 1930: Famous letter to the “Dear radioactive ladies and gentlemen” (see left).
- Reason: In $\beta$-decay only two particles seen, but continuous energy spectrum of the electron. Impossible in two-body decays.
Naive question: Nuclei made from protons and neutrons. Why do they stick together (despite electromagnetic repulsion)?

Answer: Existence of a strong nuclear force.

In nuclei, this is realised by exchange of pions as force carriers.

Later we will see that they are bound states of a quark-antiquark pair \((q\bar{q})\), while the nucleons are bound states of 3 quarks, \(qqq\).

Strong force mediated by massless spin-1 gluons.

The charge related to it is called colour - quarks come, e.g. in three colours, while the 8 gluons carry a colour-anti-colour each.

Quantum ChromoDynamics (QCD)
Symmetries in classical physics

Invariance and conservation laws

- From classical physics it is known that invariance of a system under certain transformations is related to the conservation of corresponding quantities.

- Examples:

<table>
<thead>
<tr>
<th>Invariance under</th>
<th>Conserved quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>rotations</td>
<td>angular momentum</td>
</tr>
<tr>
<td>time translations</td>
<td>energy</td>
</tr>
<tr>
<td>space translations</td>
<td>momentum</td>
</tr>
</tbody>
</table>

- Formalised by Emmy Noether (thus: Noether’s theorem)
Invariance and conservation laws

- The same ideas work also in quantum physics:
  Invariances give rise to conservation laws.

- There, however, internal symmetries also play a role.
  In fact, they are used to construct interactions in theories.

- Example:
  
  - Invariance under phase transformations of the fields
    \[ \psi(x, t) \rightarrow \psi'(x, t) = \exp(i\theta)\psi(x, t) \iff |\psi|^2 = |\psi'|^2 \]
    yields conserved charges like, e.g., the electrical charge.
  - The photon field couples to this charge and is thus related to the invariance under such phase transitions (later more).
Ideas of symmetry are formalised in group theory.

Definition of groups:
- Consider sets of elements $S = \{a, b, \ldots\}$ with operation “·” $a \cdot b$.
- Such sets are called groups, if
  - $a \cdot b \in S$ (closure)
  - $a \cdot (b \cdot c) = (a \cdot b) \cdot c$ (associativity)
  - $\exists 1 \in S: a \cdot 1 = 1 \cdot a = a \ \forall a \in S$ (neutral element)
  - $\forall a \in S: \exists a^{-1} \in S$ such that $a \cdot a^{-1} = a^{-1} \cdot a = 1$ (inverse element).

Examples: $S = $ integer numbers, $\cdot = +$, rotations with arbitrary angles, the set $\{1, 2, 3, \ldots, p - 1\}$ under multiplication modulo $p$, if $p$ is a prime number, ...
Consider two slabs with quadratic and round cross section. The quadratic one has a discrete symmetry w.r.t. rotation along its axis, while the round one enjoys a continuous symmetry.
Important discrete symmetries

A prime example: Parity

- Parity is invariance under
  \[ \psi(\vec{x}, t) \leftrightarrow \hat{P} \psi(\vec{x}, t) = \lambda \psi(-\vec{x}, t) : \]
- This translates into \( |\psi(\vec{x}, t)|^2 = |\psi(-\vec{x}, t)|^2. \)
- Therefore, \( \lambda = \pm 1 \) corresponding to even (+) or odd (-) parity.
- If a force (e.g. electromagnetism) respects parity, parity even states cannot emerge during interaction from odd states and vice versa.
- Note: Electron orbits in an atom have a defined parity.
- In addition, particles have **intrinsic** parity.
- Parity is multiplicative.
Parity at work

 Atomic physics example:
Since orbitals have definite parity and because electrodynamics respects parity, not all transitions are allowed. This manifest itself in “missing” spectral lines (although the orbitals exist and the transition is energetically allowed): Parity selects allowed transitions.

 Particle physics example:
A $J/\psi$ is a vector particle, it therefore has $P = -1$. If it decays into two particles, they must always form an $s$-wave (even parity). To see this consider the c.m. system of the decaying particle - the two outgoing ones are back-to-back with no angular momentum. Therefore a decay of a vector into two vectors is forbidden.
Further discrete symmetries

- **Time reversal:** Invariance under
  \[ \psi(\vec{x}, t) \longleftrightarrow \hat{T}\psi(\vec{x}, t) = \psi(x, -t) \]

- **Charge conjugation:** Invariance under
  \[ \psi_{e-}(\vec{x}, t) \longleftrightarrow \hat{C}\psi_{e-}(\vec{x}, t) = \psi_{e+}(x, t) \]

- **The \textit{CPT}-theorem:**
  This theorem assures that theories and physics are invariant under the combined action of \( \hat{C} \), \( \hat{P} \) and \( \hat{T} \), although individual forces may break invariance of individual discrete symmetries or even their products.
Summary

- Feynman diagrams as terms in the perturbative expansion of the transition amplitude between states.
- Short introduction of how to construct Feynman diagrams.
- Briefly reviewed the four fundamental forces in nature: Gravitational, electromagnetic, weak and strong.
- Introduced symmetries (continuous vs. discrete).
- To read: Coughlan, Dodd & Gripaios, “The ideas of particle physics”, Sec 5-6.