Introduction to the Standard Model

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Outline

- Particle content
- Quantum Field Theory
- Electromagnetic Interactions
- The Higgs mechanism
- Quantum Chromodynamics
- Gravitational Interactions
- Feynman diagrams

Introduction

Particles physics seeks to answer two questions:

- What are the fundamental (smallest) building blocks from which all matter is made?
- What are the interactions between them that govern how they combine and decay?

- Standard Model (SM): name given to the theory that best incorporates all observations to date in particle physics
- SM describes the strong, weak and electromagnetic interactions of all particles
- Triumph of the 70's
- All measurements are in agreement with predictions obtained from SM

Particle Content

- Particles are divided into two classes on the basis of their spin
- for fundamental particles spin is an intrinsic and inherently quantum property, it can not be understood in terms of motions internal to the object
- Bosons are particles with integer spin in units of Planck constant
- Fermions are particles with on odd number of half integer units of spin (1/2, 3/2, 5/2…)
- Fermions obey the Pauli exclusion principle – no two of the same type can exist in the same state at the same place and time
- Bosons do not follow such rules
- Matter particles are fermions
- Force carrier particles are bosons

Forces and Interactions

- All forces between objects are due to interactions
- All particles decays are due to interactions
- There are four types of fundamental interactions
- Strong interactions, responsible for forces between quarks and gluons
- Electromagnetic interactions, responsible for electric and magnetic forces
- Weak interactions, responsible for instability of all but the least massive fundamental particles in any class
- Gravitational interactions, responsible for forces between any two objects due to their energy

Forces Carriers

- Each type of interactions has a characteristic set of force carrier particles
- Gluons are the carrier particles of the strong interactions
- Photons are the carrier particles of electromagnetic interaction
- W and Z bosons are the carrier particles of weak interactions
- Graviton is the name of the carrier particle of the gravitational interaction. The status of this particle is still tentative. Gravitons are not considered to be part of the Standard Model

Real and virtual particles

- Particles that can be observed either directly or indirectly in experiments are real particles
- Virtual particles are a language invented by physicists in order to talk about processes in terms of Feynman diagrams
- Feynman diagrams are a shorthand for a calculation that gives the probability of the process

Cross sections

- The cross section is the probability that an interaction will occur between a projectile particle and a target particle
- We can picture the cross section as the effective area that a target presents to the projected particle. If an interaction is highly probable, it's as if the target particle is large compared to the whole target area, while if the interaction is very rare, it's as if the target is small.
- The cross section for an interaction to occur does not necessarily depend on the geometric area of a particle.
- Cross sections depend on the type of interactions and on the amount of energy that is converted from mass energy to kinetic energy

Decay rates

- Any decay that can happen will happen!
- Decays can happen only if all conservation laws are respected
- Conservation of energy (decay into lighter particles)
- Conservation of charge, baryon number, electron number

Quantum mechanics

- Systems are described by the set of possible states in which they may be found
- Bound states are labeled by a set of quantum numbers, that define the various conserved quantities associated with the state
- A label is a pure number, that counts discrete quantities such as electric charge, energy, angular momentum etc.
- The probability of finding a particle described by a wave function at a given point is proportional to the square of the absolute value of the probability amplitude
- Everything comes in small packages of unit Planck constant

Quantum field theory

- Is the application of quantum mechanics to dynamical systems of fields
- In the same sense that quantum mechanics is concerned with the quantization of dynamical systems of particles
- Given that we wish to understand processes that occur at very small (quantum mechanical) scales at very large (relativistic) energies we need a multiparticle theory
- Particle creation and annihilation due to Einstein $E = mc^2$
- Masses in high energy physics are given in units of energies

Electroweak Interactions

- Unification of electromagnetic and weak interactions
- Fundamental electromagnetic interactions occur between any two particles that have charge
- Photons are the carrier particles of electromagnetic interactions
- Fundamental weak interactions occur for all fundamental particles except gluons and photons
- Weak interactions involve the exchange or productions of W or Z bosons (massive)
- Weak forces are very short-ranged
- Weak decays are responsible for the fat that ordinary stable matter contains only up and down type quarks and electrons (the lightest fundamental particles)

Higgs mechanism

- Gauge principle leads to theories in which all the interactions are mediated by massless vector bosons
- One part of the SM is not yet well established:
- We do not know what causes the fundamental particles to have masses!
- The simplest idea is called the Higgs mechanism, involving one new particle, called the Higgs boson, and one additional force type, mediated by exchanges of this boson
- The Higgs particle has not yet been observed
- This part of the theory is the least tested experimentally, so there are a number of different competing ideas of how it may work

Strong interactions

- Fundamental strong interactions occur between any two particles that have colour charge
- There are three possible colour charges for quarks
- There are three different anti-colour for antiquarks
- Gluons have one colour and one anti-colour, there are 8 possible different combinations
- All observed particles are colour-neutral objects
- Quarks and gluons are only found inside hadrons (mesons qqbar, and baryons qqq), we say they are confined
- Quantum Chromo Dynamics (QCD) non-abelian gauge theory based in SU(3)
- Asymptotic freedom: coupling constant g_s small at high energies (only there perturbation theory is valid)

Gravitational Interactions

- Between any two objects that have energy
- mass is just one possible form of energy, photons are massless but they experience gravitational forces
- 10^{-30} times weaker then weak interaction
- No Quantum field theory of gravitational interactions has been successfully identified
- Understand big bang, need to understand quantum gravity, gravitational interactions are comparable in strength to other particle interactions
- Need theory to treat both
- String theory most promising approach (7 extra space dimensions)

Feynman diagrams

- The diagrams Richard Feynman introduced provide a convenient shorthand for the calculation
- Every line in the diagram represents a particle
- Any vertex represents an interaction
- Conservation of energy is required at every vertex
- Lines entering or leaving the diagram represent real particles
- Lines in intermediate stages in the diagram represent virtual particles
- No single vertex diagram represents a possible process
- Each diagram has a definite complex number quantity – called amplitude – related to it by a set of rules (Feynman rules)
- Power series expansion in the coupling parameter