# Complete Particle Physics

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May 4, 2026

## Contents

# 1 Historical Introduction to the Elementary Particles

## 1.1 Core ideas

Particle physics grew from cosmic rays, nuclear physics, accelerators, and the discovery of hadrons, leptons, quarks, neutrinos, and gauge bosons. The modern picture is the Standard Model: matter fermions interacting through gauge fields, with masses from electroweak symmetry breaking.

For review, be able to name the Standard Model particles, distinguish leptons, quarks, gauge bosons, and hadrons, and explain why accelerators probe short distances. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

## 1.2 Mathematical spine

$$\Delta x \sim \hbar/\Delta p, \qquad \text{SM gauge group} = SU(3)_C \times SU(2)_L \times U(1)_Y$$

**Section summary** The Standard Model organizes the particle zoo into fields and symmetries.

# 2 Elementary Particle Dynamics

## 2.1 Core ideas

Scattering and decay experiments measure probabilities from amplitudes. Cross sections, decay rates, luminosity, phase space, and matrix elements connect theory to event counts. Relativistic normalization and conservation laws constrain every process.

For review, be able to compute event-rate relations, distinguish cross section and decay width, and use phase space qualitatively. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

## 2.2 Mathematical spine

$$dN = \mathcal{L}\sigma\, dt, \qquad d\Gamma = \frac{1}{2M}|\mathcal{M}|^2 d\Phi_n$$

**Section summary** Dynamics is inferred from scattering rates and decay probabilities.

# 3 Relativistic Kinematics

## 3.1 Core ideas

Particle reactions obey four-momentum conservation. Mandelstam variables, invariant masses, thresholds, rapidity, and center-of-mass frames make high-energy reactions frame independent.

For review, be able to use invariant mass, threshold conditions, Mandelstam variables, and two-body kinematics. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

## 3.2 Mathematical spine

$$s = (p_1 + p_2)^2, \qquad t = (p_1 - p_3)^2, \qquad u = (p_1 - p_4)^2$$

**Section summary** Relativistic invariants are the language of collisions.

# 4 Symmetries

## 4.1 Core ideas

Symmetries classify particles and constrain interactions. Continuous symmetries give conserved charges; discrete symmetries include parity, charge conjugation, and time reversal. Gauge symmetry is not optional decoration: it determines interactions.

For review, be able to apply Noether reasoning, identify internal quantum numbers, and distinguish global from gauge symmetries. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

## 4.2 Mathematical spine

$$\partial_\mu j^\mu = 0, \qquad Q = \int j^0 \, d^3x$$

**Section summary** Symmetries determine conservation laws and allowed processes.

# 5 Bound States and the Quark Model

## 5.1 Core ideas

Hadrons are bound states of quarks and gluons. Mesons are quark-antiquark states, baryons contain three valence quarks, and flavor symmetry organizes multiplets. Color confinement prevents isolated quarks.

For review, be able to construct basic meson and baryon quantum numbers, use flavor multiplets, and explain color singlets. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

## 5.2 Mathematical spine

$$q\bar{q}\ \text{meson}, \qquad qqq\ \text{baryon}, \qquad \text{physical states are color singlets}$$

**Section summary** The quark model organizes hadron spectroscopy.

# 6 Feynman Calculus and QED Processes

## 6.1 Core ideas

Feynman diagrams encode perturbative amplitudes. In QED, vertices couple charged fermions to photons; propagators describe virtual particles; spin sums and phase space produce cross sections.

For review, be able to translate simple diagrams to amplitudes, identify propagators and vertices, and know standard QED processes like annihilation and Compton scattering. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

## 6.2 Mathematical spine

$$\mathcal{L}_{\text{QED}} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \bar{\psi}(i\gamma^\mu D_\mu - m)\psi, \qquad D_\mu = \partial_\mu + ieA_\mu$$

**Section summary** QED is the prototype precision gauge theory.

# 7 Weak Interactions

## 7.1 Core ideas

Weak interactions change flavor and violate parity. Charged currents involve $W^{\pm}$, neutral currents involve $Z$, and low-energy weak processes are described by Fermi theory. Neutrino mixing shows that flavor and mass eigenstates differ.

For review, be able to describe beta decay, charged and neutral currents, parity violation, CKM/PMNS mixing, and the Fermi limit. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

## 7.2 Mathematical spine

$$\mathcal{L}_{\text{Fermi}} \sim -\frac{G_F}{\sqrt{2}} J_\mu^\dagger J^\mu, \qquad G_F/\sqrt{2} = \frac{g^2}{8M_W^2}$$

**Section summary** Weak interactions are short-range, chiral, and flavor-changing.

# 8 Gauge Theories and the Standard Model

## 8.1 Core ideas

The Standard Model is a renormalizable gauge theory with spontaneous electroweak symmetry breaking. Gauge symmetry fixes the interactions; the Higgs field gives masses while preserving consistency at high energy.

For review, be able to state the gauge group, identify representations, explain Higgs mechanism, and connect masses to couplings. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

## 8.2 Mathematical spine

$$SU(3)_C \times SU(2)_L \times U(1)_Y \to SU(3)_C \times U(1)_{\text{em}}$$

**Section summary** The Standard Model is a symmetry-based quantum field theory.

# 9 QCD and Hadron Spectroscopy

## 9.1 Core ideas

QCD is the non-Abelian gauge theory of color. Asymptotic freedom makes quarks weakly coupled at high momentum; confinement and chiral symmetry breaking dominate low-energy hadrons. Jets reveal quarks and gluons experimentally.

For review, be able to explain color, running coupling, confinement, asymptotic freedom, jets, and hadron multiplets. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

### 9.2 Mathematical spine

$$\alpha_s(Q^2) \sim \frac{1}{\ln(Q^2/\Lambda_{\text{QCD}}^2)}, \qquad \mathcal{L}_{\text{QCD}} = -\frac{1}{4}G^a_{\mu\nu}G^{a\mu\nu} + \bar{q}(i\gamma^\mu D_\mu - m)q$$

**Section summary** QCD explains strong interactions through color gauge fields.

## 10 Beyond the Standard Model

### 10.1 Core ideas

The Standard Model is incomplete: it omits gravity, dark matter, baryon asymmetry, and a full explanation of neutrino masses and hierarchy. Effective field theory parameterizes possible heavy physics without knowing its details.

For review, be able to state major open problems, use EFT logic, and distinguish direct, indirect, and cosmological probes. Keep the physical question visible: identify the degrees of freedom, the conserved quantities, the approximation being made, and the observable that would be measured.

### 10.2 Mathematical spine

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^{d_i-4}}\mathcal{O}_i$$

**Section summary** Beyond-Standard-Model physics is constrained by symmetry, scales, and precision data.