Particle Physics Junior Honours Study Guide

This is a guide of what to revise for the exam. At the end is a list of the equations you need to remember, and a summary of the forces and Feynman rules.

Quarks, Leptons and Quantum Numbers

The quarks and leptons (a.k.a. the fermions) and their anti-particles. Which ones interact under which force(s).

The definition of the following quantum numbers and if they conserved or violated by the different forces.

- Electric charge, Q.
- Baryon number, $\mathcal{B}$.
- Lepton numbers: L_e, L_μ, L_τ
- Strangeness (S), Charmness (C), Bottomness (B), Topness (T) and Isospin (I_Z). For these it's enough to remember these represent the net number of quark minus anti-quarks for each quark flavour.
- Colour charge.

Forces

There is a summary of the forces at the end of this guide.

- The three forces we have to consider in particle physics: strong, electromagnetic and weak; which bosons propagate the forces.
- The coupling constants (in symbols); the relative strength of the forces.
- The allowed flavour changes for W-boson interactions. (The flavour of the quarks and leptons is conserved in interactions with the other bosons.)

Scattering and Decay

These are the two main types of measurements we make in particle physics to explore the fermions and the interactions between them. (There are some equations describing decays and scattering in the equation section.)

- Elastic collision and inelastic collisions.
- Rough lifetimes for decays due to the different forces.
- Which particles don't decay, and why.

Experiments and Detectors

Briefly. . .

- What are fixed target experiments and collider experiments. Why are colliders better at producing high mass particles?
- What is a synchrotron and a linear accelerator (linac). How are particles accelerated in them? Which particles are usually used in collider experiments?
- How charged particles appear in a detector.
- How electrons, muons and photons appear in a detector.
- Quarks signals in a detector *i.e.* hadronisation.

Mesons and Baryons

What is a hadron, a meson and a baryon, and why are quarks are confined to them?

Relativistic Dynamics

- Conservation of four-momentum! Especially important for calculating the boson four momentum, $\underline{\underline{q}}$, in the boson propagator terms. Also important in decays and scattering.
- Decays: when can they occur? Branching fractions, how to calculate the widths of the individual decay modes and the total width (see equations).

Natural Units

- We set $\hbar = c = 1$. The most important implication of this is that mass, momentum and energy are all measured in units of energy, usually MeV or GeV.

Feynman Diagrams and Feynman Rules

How to draw simple Feynman diagrams, and how to calculate $\mathcal{M}$. (Simple means diagrams with just one, or maybe two, bosons). What is a virtual boson?

Concepts

- What is anti-matter, how is it related to the matter particles, and how can we interpret anti-matter?

Equations

This is a list of equations you need to know! Note some of the equations use specific collisions and decays as examples; the equations, however, apply to all types of collisions and decays.

- The four momentum of a particle, in natural units is:

$$\underline{\underline{p}} = (E, p_x, p_y, p_z) = (E, \vec{p}) \tag{1}$$

where E is the energy, and $\vec{p}$ is the three momentum.

- The square of the four momentum of any initial or final state particle is its mass squared:

$$\underline{\underline{p}}^2 = E^2 - \vec{p} \cdot \vec{p} = m^2 \tag{2}$$

This is not necessarily true for bosons propagating an interaction. If $\underline{\underline{q}}^2_{\text{boson}} \neq m^2_{\text{boson}}$ we say the boson is *virtual.*

- The Lorentz Transformations in natural units are:

$$\gamma = E/m \;\Rightarrow\; E = \gamma m \qquad \beta = |\vec{p}|/E \qquad \gamma\beta = |\vec{p}|/m \tag{3}$$

- In a collision (at a collider or fixed target) the centre of mass energy is $\sqrt{s}$, where s is the square of the sum of the four-mometum of the colliding particles. *e.g.* for an $e^+ + e^-$ collision:

$$s = (\underline{\underline{p}}_{e^+} + \underline{\underline{p}}_{e^-})^2 \tag{4}$$

- The total width of a particle (Γ) and the lifetime of the particle (τ) are related as:

$$\Gamma = \hbar/\tau \tag{5}$$

- The branching fractions of a decay is, *e.g.*:

$$\text{BF}(\tau^- \to e^-\bar{\nu}_e\nu_\tau) = \frac{\Gamma(\tau^- \to e^-\bar{\nu}_e\nu_\tau)}{\Gamma_\tau} \tag{6}$$

where $\Gamma(\tau^- \to e^-\bar{\nu}_e\nu_\tau)$ is the width of individual decay $\tau^- \to e^-\bar{\nu}_e\nu_\tau$.

- The width of individual decay modes are proportional to $\mathcal{M}^2$, *e.g.*

$$\Gamma(\tau^- \to e^-\bar{\nu}_e\nu_\tau) \propto \left(\mathcal{M}(\tau^- \to e^-\bar{\nu}_e\nu_\tau)\right)^2 \tag{7}$$

The total width of a particle is the sum of width of all possible decay modes:

$$\Gamma_\tau = \Gamma(\tau^- \to e^-\bar{\nu}_e\nu_\tau) + \Gamma(\tau^- \to \mu^-\bar{\nu}_\mu\nu_\tau) + \Gamma(\tau^- \to \text{hadrons} + \nu_\tau) \tag{8}$$

- The cross section, σ, of a scattering is proportional to the matrix element squared: $\mathcal{M}^2$, *e.g.*

$$\sigma(e^+e^- \to \mu^+\mu^-) \propto \left(\mathcal{M}(e^+e^- \to \mu^+\mu^-)\right)^2 \tag{9}$$

What you don't have to remember

If you need any of these, they will be given!

- The masses of all the particles; in an exam they are given on the constant sheet.
- The lifetimes of all the particles.
- The quark content of all the hadrons.
- The names of the accelerators and experiments, which particles and energies they use.

QED	QCD	Weak Neutral Current	Weak Charged Current
quantum theory of EM interactions	quantum theory of strong interactions	quantum theory of weak interactions	
mediated by exchange of virtual photons	mediated by exchange of gluons	mediated by exchange of Z bosons	mediated by exchange of W bosons
acts on all charged particles	acts on quarks only	acts on **all** quarks and leptons	
couples to electric charge	couples to colour charge	does not change quark or lepton flavour	changes quark and leptons flavours
coupling strength ∝ fermion charge ∝ $e \propto \sqrt{\alpha}$	coupling strength ∝ $g_S \propto \sqrt{\alpha_S}$ (equal for all quark flavours)	coupling strength ∝ g'_W	coupling strength ∝ $g_W \propto \sqrt{\alpha_W}$ at lepton vertex: g_W at quark vertex: $g_W V_{qq'}$
photon propagator: $1/q^2$	gluon propagator: $1/q^2$	Z-boson propagator: $1/(q^2 - M_Z^2)$	W-boson propagator: $1/(q^2 - M_W^2)$