An Introduction to High Energy Physics

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Useful references:

Particle Physics Booklet (available free!)
D. Perkins, Intro. to High Energy Physics (Addison-Wesley)
P.C.W. Davies, The Forces of Nature (Cambridge U. Press)
F. Close, The Cosmic Onion (Heinemann)
R. Feynman, QED (Penguin)

Particle Physics Booklet

- Latest listings and properties of all known particles and searches for hypothetical ones.
- New edition June 2002.
- One copy is available for free either:
  - On the web at http://pdg.lbl.gov/pdgmail
  - Via email from pdgrequest@lbl.gov
  - By postal mail:

    Particle Data Group, MS 50R6008
    Lawrence Berkeley National Lab
    One Cyclotron Road
    Berkeley, CA 94720-8166 USA

What is High Energy Physics?

- High Energy physics explores objects that are not only very energetic but are also very small.
- We probe the fundamental structures of matter and energy and the interplay between them.
- Ultimately, we want to describe the Elementary Particles and their interactions - hence the alternative name, "Particle Physics".
- We discover new laws of Nature with exquisite mathematical beauty.
  (Actually, much of the relevant mathematics had been considered purely esoteric until their use here).

Small and Energetic

These tell us what theories we should use for our physics.

- "Small" means that QUANTUM MECHANICS is important, where particles tend to behave more like waves, according to de Broglie's formula:

$$\text{wavelength} = \frac{h}{\text{momentum}} \qquad \textit{or} \qquad \lambda = \frac{\hbar}{p}$$

  $\hbar$ is Planck's constant and small, 6.63×10^{-34} Js.

- "Energetic" means that SPECIAL RELATIVITY is important, and we should use Einstein's equation:

$$E = \sqrt{(mc^2)^2 + (pc)^2}$$

  c is the vacuum speed of light and large, 3.0×10^8 m/s.

What do we mean?

- Perusing the Particle Physics Booklet one finds, for example:

"…yields an average W-boson mass of 80.4 GeV …"

Why is a mass being reported in units of energy?

$[1\ \mathrm{GeV} = 10^9\ \mathrm{eV} = 1.6 \cdot 10^{-10}\ \mathrm{J}]$

- Similary, why is the "radius" of the proton often approximated by $4\ \mathrm{GeV}^{-1}$?

Why is a length represented by an inverse energy?

Units

The traditional set of units that we are most familiar with is $\{M, L, T\}$. In terms of these, the dimensions of our three important quantities in High Energy Physics are:

$$[c] = [\text{velocity}] = LT^{-1}$$
$$[\hbar] = [\text{length} \times \text{momentum}] = ML^2T^{-1}$$
$$[E] = [\text{mass} \times \text{velocity}^2] = ML^2T^{-2}$$

However, now we realize that we can invert these relationships so that the set $\{M, L, T\} \longrightarrow \{c, \hbar, E\}$:

$$\begin{aligned} L &= [\hbar][c][E]^{-1} \\ M &= [E][c]^{-2} \\ T &= [\hbar][E]^{-1} \end{aligned}$$

Translations

At this point, we decide to set $\hbar = c = 1$, with the understanding that since they have different dimensions we can always reinstate them in formulae uniquely using dimensional analysis. So the new dimensions are:

$$\begin{aligned} \text{length} &\sim L = [\hbar][c][E]^{-1} \to [E]^{-1} \\ \text{mass} &\sim M = [E][c]^{-2} \to [E] \\ \text{lifetime} &\sim T = [\hbar][E]^{-1} \to [E]^{-1} \end{aligned}$$

- So a mass of 80.4 GeV really means 80.4 GeV/c^2 and,
- a proton radius of $4\ \text{GeV}^{-1}$ is really $r = 4\ (\hbar c)\ \text{GeV}^{-1}$:

$$\begin{aligned} r &= 4 \times \left(6.63 \cdot 10^{-34}/(2\pi) \times 3 \cdot 10^{8}\right) / 1.6 \cdot 10^{-10} \\ &= 8 \cdot 10^{-16}\ m \end{aligned}$$

High Energy Accelerators - Theory

Let's go back to Einstein's equation, where we have now set $c = 1$, so $E = \sqrt{m^2 + p^2}$. This suggests a strategy for searching for new heavy types of matter:

1. Start with two fairly light particles of mass $m_{\rm small}$.
2. Accelerate them so that they each obtain large momenta $p_{\rm large}$ and energies $E = \sqrt{m_{small}^2 + p_{large}^2}$.
3. Set the particles on a collision course and wait!
4. When they are close together they may interact in such a way that a new particle is produced with almost zero momentum. However, energy must be conserved so that the mass of the new particle m is:

$$m = 2E = 2\sqrt{m_{small}^2 + p_{large}^2}$$

Accelerators in Practice

- In practice, this ideal scenario is hard to accomplish – for example, many new particles may be produced (not just one).
- Our near neighbours at Fermilab accelerate protons and anti-protons in their Tevatron collider.

$$m_{\rm proton} \approx 1 \text{ GeV}$$
$$E_{\rm total} = 2 \text{ TeV} = 2000 \text{ GeV}$$

- Physicists there discovered the heaviest elementary particle yet found - the top quark with mass 175 GeV.
- The Tevatron is the highest energy collider in the world at present - until the Large Hadron Collider (LHC) switches on in 2005, with $E_{\rm total} = 14 \text{ TeV}$.

The Uncertainty Principle

The higher the energy that a particle has, the shorter the distance that it travels and the shorter it lives.

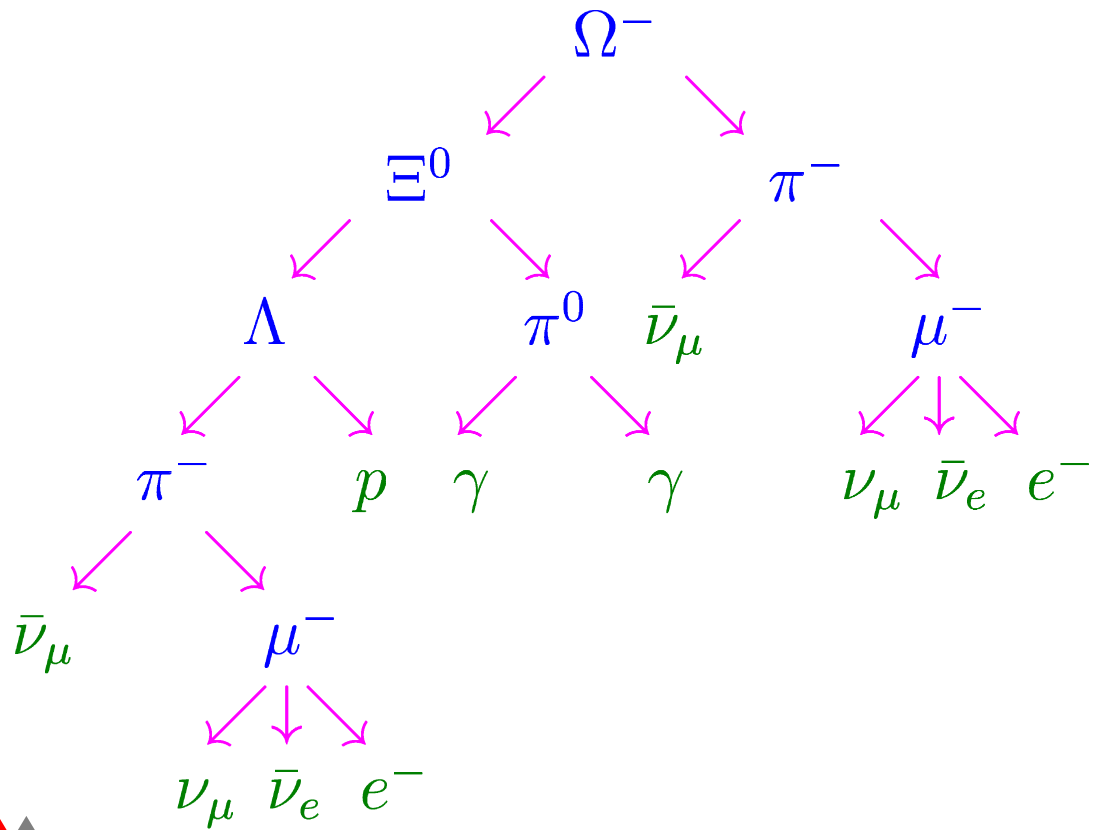
- Many of the particles that we produce in a high energy collision are unstable and do not live for very long
- For instance, the top quark is not seen directly, but is observed via its multi-stage decay:

$$\begin{aligned} \text{top quark } (t) \longrightarrow \;\; & \text{W boson } (W^+) \;\; + \;\text{bottom quark } (b) \\ & \hookrightarrow \;\; \text{positron } (e^+) + \text{neutrino } (\nu_e) \end{aligned}$$

- Part of the challenge of experimental high energy physics is figuring out exactly where all the particles came from!

The Ω^-

The particle known as the Ω^- was a successful prediction of the theory that is now universally embraced by high-energy physicists.



The Electromagnetic Spectrum

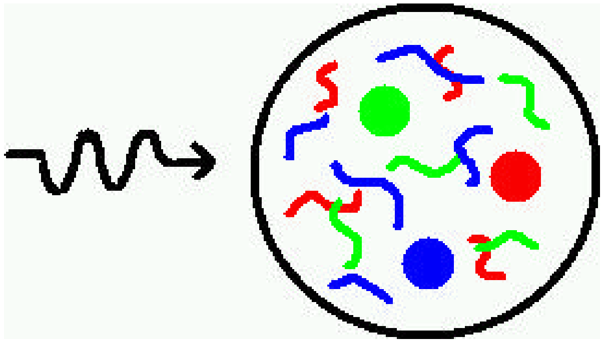
$E = \frac{hc}{\lambda} \Longrightarrow$ high energy = short wavelength

Region	Wavelength (m)	Energy (eV)
Radio	> 0.1	$< 10^{-5}$
Microwave	$0.1 - 10^{-4}$	$10^{-5} - 0.01$
Infrared	$10^{-4} - 7 \cdot 10^{-7}$	$0.01 - 2$
Visible	$7 \cdot 10^{-7} - 4 \cdot 10^{-7}$	$2 - 3$
Ultraviolet	$4 \cdot 10^{-7} - 10^{-9}$	$3 - 10^{3}$
X-Rays	$10^{-9} - 10^{-11}$	$10^{3} - 10^{5}$
Gamma Rays	$< 10^{-11}$	$> 10^{5}$
Tevatron	10^{-18}	10^{12}
LHC	$2 \cdot 10^{-19}$	$0.7 \cdot 10^{13}$

Particle Probes

To resolve an object, we must “look” at it with particles which have a wavelength less than the objects size.

- Size of an atom ~ 0.2 nm $= 2 \cdot 10^{-10}$m.
  $\hookrightarrow$ X-Ray diffraction
- Size of the nucleus of Uranium-238 $\sim 10^{-14}$m.
  $\hookrightarrow$ Nuclear physics
- Size of the proton $\sim 10^{-15}$m.
  $\hookrightarrow$ High-energy physics
  $\downarrow$
  nuclear sub-structure
  $\downarrow$
  quarks



- Size of a quark $\sim$????.

Particle Properties

Just as with atoms, it is possible to group the elementary particles that we know about into families with similar properties. First we need to know:

- Which particles are truly elementary?
  Stable: p, n, $e^{\pm}$, γ, ν
  Unstable: $W^{\pm}$, t, Ω^{-}, Ξ^{0}, Λ, π
- What characteristics do they share?
  - Mass?
  - Electric charge?
  - Something else we don't know about?

The Periodic Table of HEP

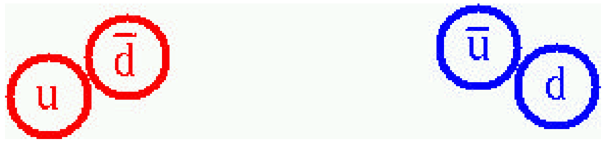
	Matter (fermions)				Radiation			
	leptons		quarks		bosons			
charge	-1	0	$+2/3$	$-1/3$	0	0	± 1	0
interactions ↓	e^- μ^- τ^-	ν_e ν_μ ν_τ	u c t	d s b	g	γ	$W^\pm$	Z^0
strong			X	X	$\star$			
electromagnetic	X		X	X		$\star$		
weak	X	X	X	X			$\star$	$\star$
gravitational	X	X	X	X	X	X	X	X

. . . plus the fermions' anti-particles, with opposite charge.

Hadrons and confinement

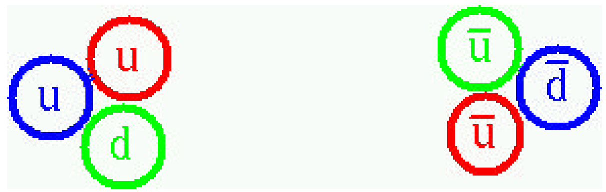
- We don't see quarks and gluons directly, because the strong colour interaction confines them into hadrons.

mesons - $(q\bar{q})$



e.g. pion, π^+, $u\bar{d}$ (charge = $+2/3 + 1/3 = +1$)
kaon, K^0, $d\bar{s}$ (charge = $-1/3 + 1/3 = 0$)

baryons - (qqq) or $(\bar{q}\bar{q}\bar{q})$

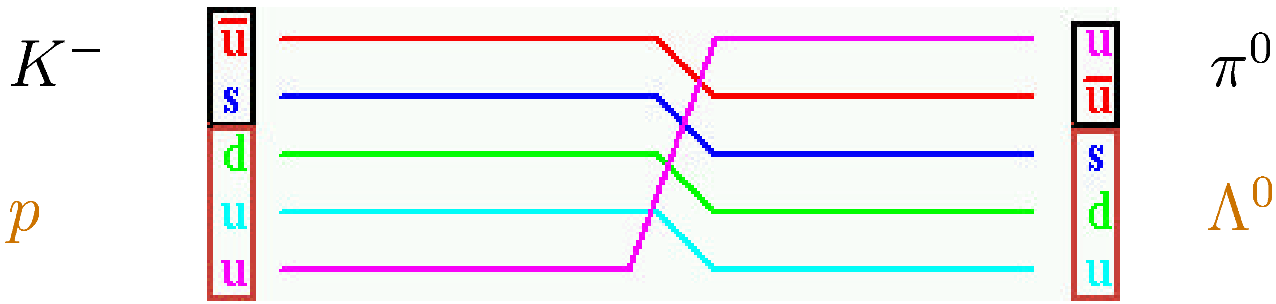


e.g. proton, uud (charge = $2/3 + 2/3 - 1/3 = +1$)
neutron, udd (charge = $2/3 - 1/3 - 1/3 = 0$)

Conservation Laws

- By writing out the quark content of baryons and mesons it is easy to decide what types of reactions are allowed.
- We are used to the conservation of electric charge and must augment this with a few more laws – such as conservation of “strangeness” under the strong force.

e.g. $K^- \; (\bar{u}s) + p \; (uud) \longrightarrow \Lambda^0 \; (uds) + \pi^0 \; (u\bar{u})$



Forces of Nature

Let's compare the forces at energies (and distances) typical for HEP, say $E \sim 1$ GeV ($r \sim 0.1$ fm).

	strong	e.-m.	weak	gravity
strength	1	$\alpha = \frac{1}{137} \sim 10^{-2}$	10^{-7}	10^{-38}
lifetime(s)	10^{-23}	10^{-16}	10^{-8}	–
boson	gluons	photon	$W^{\pm}$, Z	gravitons
theory	QCD	QED		Quantum
symmetry	$SU(3)_{\mathrm{colour}}$	$U(1) \times SU(2)$		Gravity

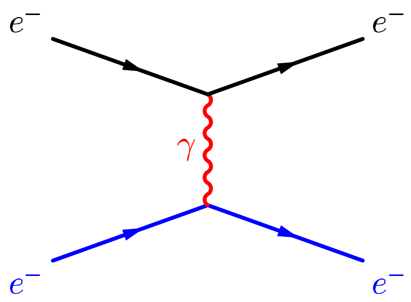
QED = Quantum Electrodynamics
QCD = Quantum Chromodynamics

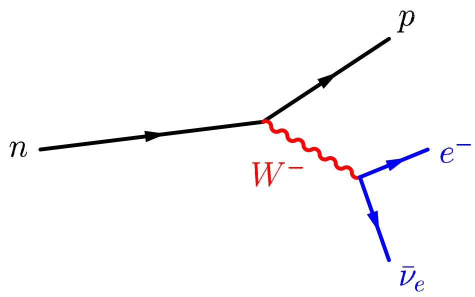
Quantum Field Theory

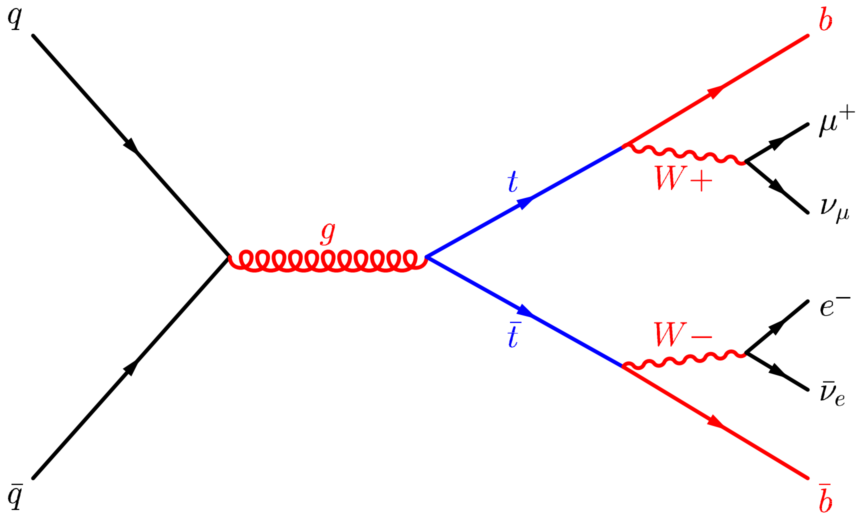
- Particles interact with each other through fields. Classically, we are familiar with electric, magnetic and gravitational fields.
- In HEP, we know that quantum mechanics is important, with the result that these fields are quantized. The particles interact by exchanging field quanta.
- These quanta are the bosons that we have been talking about - g, γ, $W^{\pm}$ and Z.
- We describe the interactions of these particles by a Quantum Field Theory (complicated math).
- Fortunately, Quantum Field Theory has a simple representation that we can use - Feynman diagrams.

Feynman Diagrams

- Simple, pretty pictures . . .
- . . . to represent all that complicated math.

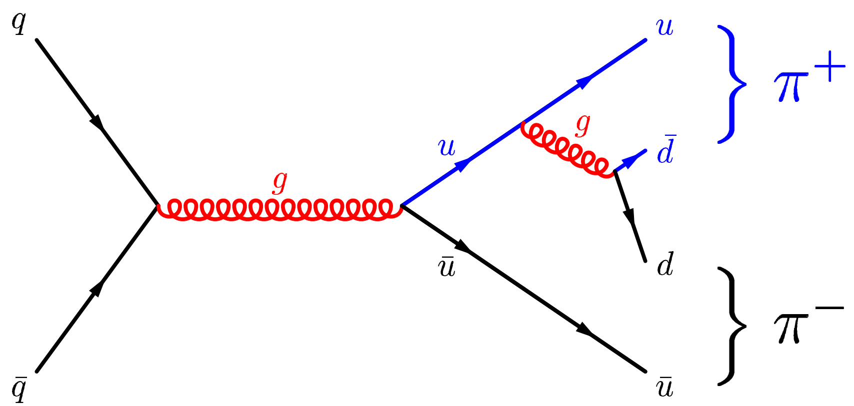






Jets

- How do hadrons form at a collider? Somehow all the quarks and gluons must rearrange themselves to become hadrons.
- The result is jets of hadrons that look very much like the paths of individual quarks.



Renormalization

According to the uncertainty principle, the vacuum may fluctuate - which causes all the field strengths and interactions to be renormalized.

This causes the strong interactions to become weaker at higher energies, called asymptotic freedom. This is the flip-side of confinement, where the interactions become stronger at lower energies (longer distances).

The Higgs Boson

The Higgs Boson is the missing link in our "periodic table", or Standard Model.

- We haven't found the Higgs yet - despite a recent false alarm at CERN.
- However, without the Higgs particle, our theory predicts that the masses of the W-boson and Z-boson are zero. This is not the case!
- The procedure by which the Higgs forces these to be massive is called Spontaneous Symmetry Breaking.
- This mechanism must happen one way or another - with a "traditional" Higgs, multiple Higgs particles, or something else. We'll know soon (maybe Tevatron, the goal of the LHC).

Super-theories

- Just as we realized that we could describe the weak and electro-magnetic theories within one embracing electroweak theory, attempts have been made to unify this theory with that of the strong interactions. These are called Grand Unified Theories, or GUTs.
- Other theorists try to link fermions and bosons through supersymmetry, introducing yet more undiscovered particles (e.g. squarks, partners of the regular quarks). These theories "naturally" incorporate gravity, leading to even more unification - supergravity.
- Ultimately, these theories may be embedded in an even more speculative framework, called superstrings. At this point we are closer to maths than physics!