Lecture 6 – The particle ZOO

Wave description of particles → interference
All components of the wave function must be the same
amplitudes may be different
True for force carriers also: Z – γ

Many (several hundred) “resonance states” observed
\( \pi^+, \pi^-, \pi^0, K^+, K^-, K^0, K^*(890), K^*(1420), N^*, \Lambda^0, \Sigma^+, \Sigma^-, \Xi \ldots \)

→ Gell-Mann + Zweig proposed Quark Model: all elementary
particles are made from smaller constituents called quarks
Until 1975 - All of the strongly interacting particles are composites of
3 quarks: up, down, strange
After 1975 – expanded to six quarks generically called flavors:
u – up, d – down, s – strange, c – charm, b – bottom, t – top

baryons: proton, neutron, ….. are made out of 3 quarks
mesons: \( \pi, K, \rho, \psi \) ….. are made out of quark – antiquark pairs
cross-section for $e^+e^-$ annihilation into hadrons

$\gamma$ virtual photon

$\sigma$ [mb] vs. cm energy, GeV
Figure 40.62: World data on the total cross section of $e^+e^- \rightarrow \text{hadrons}$ and the ratio $R(x) = \sigma(e^+e^- \rightarrow \text{hadrons}, x)/\sigma(e^+e^- \rightarrow \mu^+\mu^-)$, where $\sigma(e^+e^- \rightarrow \text{hadrons}, x)$ is the experimental cross section corrected for initial state radiation and electron-positron vertex loop contributions. $\sigma(e^+e^- \rightarrow \mu^+\mu^-)$ is given by $4\pi \alpha^2(x)/3\alpha$. Data errors are total below 2 GeV and statistical above 2 GeV. The curves are an educated guess for the broken one is a naive quark-parton model prediction and the solid one is 3-loop pQCD prediction (see "Quantum chromodynamics" section of this book). For details, see J. G. Chetyrkin et al., Nucl. Phys. B 586 (2000) 56 (Erratum ibid. B 634 (2002) 413). Brod-Wigner parameterizations of $J/\psi, \psi(2S)$, and $\Upsilon(nS), n=1,2,3,4$ are also shown. The full list of references to the original data and the details of the $R$ ratio extraction from them can be found in hep-ph/0312394. Corresponding computer-readable data files are available at http://pdg2012.lbl.gov (by courtesy of the COMPASS (Proton) and HERA/HERA(Darkness) Groups). August 2015. Corrections by T. Aalton (CERN) and M. Schmitt (Northwestern U.)
$\rho - \omega$ interference
Antiparticle – a particle with the same mass but opposite charge or magnetic property

Observations:

• gamma conversion – creation of electron + positron pair
• antiproton observed as secondary negative particle with mass equal to that of a proton, can be produced in p-p collisions
• π mesons of opposite charges produced in collisions
• resonance states of opposite charge observed in scattering and collisions resulting in multi-particle production

Problem with neutral particles:
No opposite charge - eg, π⁰, η

Explanation given by the Quark Model:
-> These particles are also their own antiparticles
Antiproton discovery (1955)

Threshold energy for antiproton ($\bar{p}$) production in proton – proton collisions

Baryon number conservation $\rightarrow$ simultaneous production of $\bar{p}$ and $p$ (or $\bar{p}$ and n)

Example: $p + p \rightarrow p + p + \bar{p} + p$

Threshold energy $\sim 6$ GeV

“Bevatron”: 6 GeV proton synchrotron in Berkeley

- build a beam line for 1.19 GeV/c momentum
- select negatively charged particles (mostly $\pi^-$)
- reject fast $\pi^-$ by Čerenkov effect: light emission in transparent medium if particle velocity $v > c / n$ ($n$: refraction index) – antiprotons have $v < c / n$
  $\rightarrow$ no Čerenkov light
- measure time of flight between counters $S_1$ and $S_2$ (12 m path): 40 ns for $\pi^-$, 51 ns for antiprotons

For fixed momentum, time of flight gives particle velocity, hence particle mass $p = mv$
Comments:

Momentum measurement in magnetic field
\[ p \text{ (GeV/c)} = 0.3 \text{ B (Tesla)} \times \rho \text{ (curvature, m}^{-1}\text{)} \]
\[ \rho = 1/R \]

Only one particle observed – second proton production implied by conservation law

Distance + timing -> velocity -> mass = p/v
Example of antiproton annihilation at rest in a liquid hydrogen bubble chamber
Conservation laws

• All massive particle, unless prevented by some rule, decay into lighter particles.
• Massless particles (photons) or very light particles (electrons, neutrinos) do not decay because all other particles are heavier.
• There are several general rules that come from mechanics and electromagnetic interactions:
  • These conservation laws are:
    conservation of energy
    conservation of momentum
    conservation of angular momentum
    conservation of charge
• If a particle decay is allowed by the above, but is not observed, we invent new conservation laws. Baryon (3 quark states) number conservation is an example of such law.
Why is the free proton stable?

Possible proton decay modes (allowed by all known conservation laws: energy – momentum, electric charge, angular momentum):

- \( p \rightarrow \pi^0 + e^+ \)
- \( p \rightarrow \pi^0 + \mu^+ \)
- \( p \rightarrow \pi^+ + \nu \)

No proton decay ever observed – the proton is STABLE

Limit on the proton mean life depends on the assumed decay mode and date:
- \( t_p > 1.6 \times 10^{33} \) years for decays to \( \mu^+ \) and \( \tau > 1.3 \times 10^{34} \) years for decays to \( e^+ \)

Invent a new quantum number: “Baryonic Number” \( B \)

- \( B = 1 \) for proton, neutron
- \( B = -1 \) for antiproton, antineutron
- \( B = 0 \) for \( e^{\pm} , \mu^{\pm} \), neutrinos, mesons, photons

Require conservation of baryonic number in all particle processes:

\[
\sum_i B_i = \sum_f B_f
\]

( \( i \): initial state particle; \( f \): final state particle)
Strangeness

Late 1940’s: discovery of a variety of heavier mesons (K – mesons) and baryons (“hyperons”) – studied in detail in the 1950’s at the new high-energy proton synchrotrons (the 3 GeV “cosmotron” at the Brookhaven National Lab and the 6 GeV Bevatron at Berkeley)

Examples of mass values
Mesons (spin = 0): $m(K^\pm) = 493.68 \text{ MeV/}c^2$ ; $m(K^0) = 497.67 \text{ MeV/}c^2$
Hyperons (spin = $\frac{1}{2}$): $m(\Lambda) = 1115.7 \text{ MeV/}c^2$ ; $m(\Sigma^\pm) = 1189.4 \text{ MeV/}c^2$
   $m(\Xi^0) = 1314.8 \text{ MeV/}c^2$; $m(X^-) = 1321.3 \text{ MeV/}c^2$

Properties
- Abundant production in proton – nucleus, p – nucleus collisions
- Production cross-section typical of strong interactions ($\sigma > 10^{-27} \text{ cm}^2$)
- Production in pairs (example: $p^- + p \rightarrow K^0 + \Lambda$; $K^- + p \rightarrow \Xi^- + K^+$)
- Decaying to lighter particles with mean life values $10^{-8} – 10^{-10}$ s (as expected for a weak decay)

Examples of decay modes
$K^\pm \rightarrow \pi^\pm \pi^0$; $K^\pm \rightarrow \pi^\pm \pi^+\pi^-$; $K^\pm \rightarrow \pi^\pm \pi^0\pi^0$; $K^0 \rightarrow \pi^+\pi^-$; $K^0 \rightarrow \pi^0\pi^0$; $\Lambda \rightarrow p \pi^-$; $\Lambda \rightarrow n \pi^0$; $\Sigma^+ \rightarrow p \pi^0$; $\Sigma^+ \rightarrow n \pi^+$; $\Sigma^+ \rightarrow n \pi^-$; $\Xi^- \rightarrow \Lambda\pi^-$; $\Xi^0 \rightarrow \Lambda\pi^0$
Figure 1.3 An example of associated production, due to the interaction at $A$ of a 4-GeV/c negative pion in a hydrogen bubble chamber: $\pi^- + p \to \Lambda + K^0$. The $\Lambda$-hyperon decays at $B$ according to $\Lambda \to p + \pi^-$, and the $K^0$-meson at $C$ according to $K^0 \to \pi^+ + \pi^-$. (Courtesy CERN.)
Comment on frequency of production and lifetime

Recall relative strength of strong, electromagnetic and weak interactions. In e.g., proton-proton collisions there is an abundant production of mesons and both baryonic and mesonic resonances. The resonances decay at a time scale of $10^{-23} \text{s}$ that we consider a typical time scale of strong interactions. The electromagnetic decays e.g., $\pi^0$ decay to two photons has a typical lifetime of $\sim 10^{-17} \text{s}$

The characteristic lifetime of particles decaying due to weak interactions is $\sim 10^{-6} \div 10^{-8} \text{s}$. These are called “long-lived” particles. A particle may have e.g., both strong and weak decays. The corresponding decay branching fractions will be inversely proportional to the ratio of the relative strength of strong and weak interactions.