Particle Physics

II. Conservation Laws

Goals

¿ Energy momentum?

¿ Conservation Laws ?

¿ Decay ?

¿ Flavour ?

S'Cool LAB

CERN

→ feel free to interrupt & ask questions

Conservation Laws

- Conservation laws are an important concept in quantum physics. They tell us that a certain quantity is conserved
- This means that its values before and after an interaction have to be the same
- For example EM charge is conserved. Not for each particle separately, but the sum of all particles' charges before an interaction has to equal the sum of all particles' charges after that interaction

Conservation Laws

- Conservation laws help us determine if a certain process can take place or not
- Example: $p + p \rightarrow n + \pi^+ + \pi^- + p$ is forbidden (initial charge is 2, final charge is 1)
- Certain laws are exact: it is believed that they always hold. Others are approximately exact (they hold in say 99% of cases), or are valid under certain conditions only (for example only when the process is without the weak force)

Conservation Laws

- Conservation of 4-momentum
- Conservation of charges (EM, weak, colour)
- Conservation of baryon number
- Conservation of lepton number (total & individual)
- Conservation of flavour
- ……

4-momentum

- Is the relativistic equivalent of classical momentum
- Relativity combines space and time, and uses 4-vectors instead of 3-vectors
- 4-momentum is a combination of energy and 3-momentum:

$$p = (E, \vec{p})$$

- The square of a 4-vector is the square of the first component minus the square of the other components:

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

4-momentum

- In the case of 4-momentum, its square equals the mass squared of the particle under consideration:

$$p^2 = m^2$$

- Combining these two formulas gives

$$E^2 = m^2 + \vec{p} \cdot \vec{p}$$

- We have used c = 1 (speed of light) as this simplifies calculations quite a lot. The correct value can be reintroduced easily:

$$E^2 = m^2 c^4 + \vec{p} \cdot \vec{p}\, c^2$$

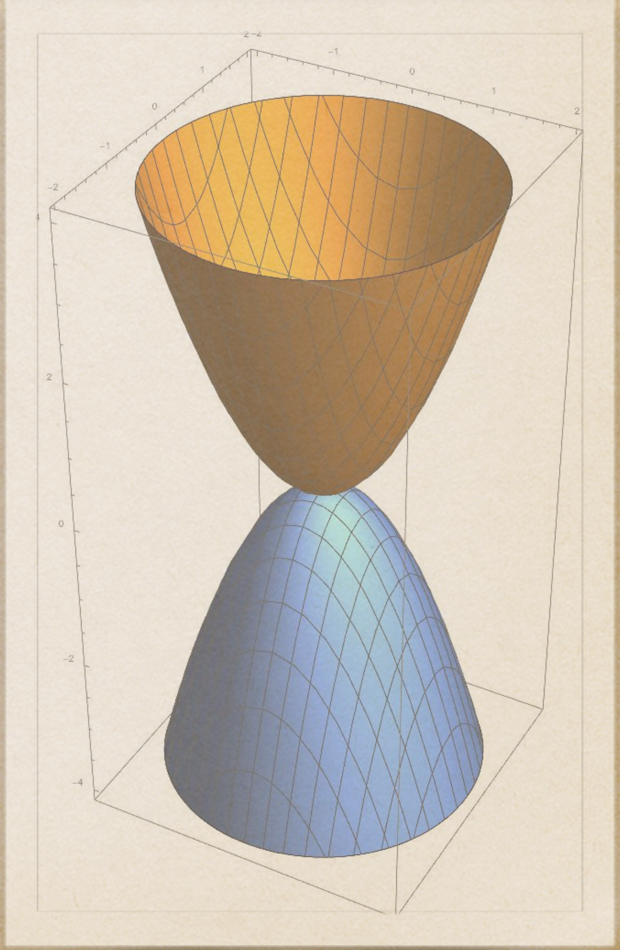
- For a particle at rest, this reduces to the famous formula

$$E = mc^2$$

4-momentum

- In particle physics, masses and momenta are always given in scaled energy units (MeV/c^2 and MeV/c), so we can safely remove all c's from the equations

- The Heisenberg uncertainty principle tells us that for a small amount of spacetime, the mass-energy relation $p^2=m^2$ can be violated. The particle is then called off-shell, or virtual



Interludium

- Gamma factor for fast-moving particle:

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}} = \frac{E}{mc^2}$$

- Time dilation and Lorentz contraction:

  $t_{LAB} = \gamma\ t_{COM}$ $L_{LAB} = 1/\gamma\ L_{COM}$

- Cosmic muons: E=6GeV, m=105MeV/c^2 => γ=57

  τ = 2.2μs —> time dilation to the rescue!

4-momentum

- 4-momentum is always conserved
- Important for decays (where one particle transforms into several). In rest frame of initial particle: mass of initial particle equals sum of energies of final particles. This gives the following condition:

$$m_{initial} \geq \sum m_{final}$$

Charge Conservation

- All charges are always 100% conserved!
- Conservation of electromagnetic charge is extremely important and an easy check of process validity
- Conservation of colour charge is automatically satisfied as long as quarks are combined correctly
- Conservation of weak charge is more complex to check, use rules of weak interaction

Weak interaction?

- Weak interaction changes flavour

- This means between one family:

  e^- <-> ν_e u <-> d   etc

- Charge is not the same => need other particles to correct this (see lecture on Feynman diagrams)

- Quarks can show mixing between families:

  u <-> s   or   u <-> b

  but probability is rather small

  No mixing between leptons!

Weak interaction?

- No other interaction can change flavour, so if we see a flavour change in a certain process, we know that this process is governed by the weak force
- We say that all interactions except the weak conserve flavour

Baryon number

- The baryon number of a system is the total number of baryons minus the total number of anti-baryons.
- Baryon number is always conserved
- Examples:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

B: 1 = 1 + 0 + 0 OK

$$p^+ \rightarrow \pi^+ + \pi^0$$

B: 1 = 0 + 0 NOK

Baryon number

- The baryon number of a system is the total number of baryons minus the total number of anti-baryons.

- Baryon number is always conserved

- Examples:

$$n \rightarrow p + e^- + \bar{\nu}_e$$

B: 1 = 1 + 0 + 0 OK

No such rule for mesons !

$$p^+ \rightarrow \pi^+ + \pi^0$$

B: 1 = 0 + 0 NOK

Lepton number

- The lepton number of a system is the total number of leptons minus the total number of anti-leptons. Similar to baryon number, lepton number is always conserved, but even per lepton family!

- Examples:

	$\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$		$\mu^- \rightarrow e^- + e^+ + e^-$	
L_e:	$0 = 1 - 1 + 0$	OK	$0 \neq 1 - 1 + 1$	NOK
L_μ:	$1 = 0 + 0 + 1$	OK	$1 \neq 0 + 0 + 0$	NOK
L :	$1 = 1 - 1 + 1$	OK	$1 = 1 - 1 + 1$	OK

Summary

- In decays, the sum of masses of final products cannot be larger than the initial mass
- EM charge is conserved
- Baryon number is conserved
- Lepton number is conserved (total & individual)
- Flavour is conserved unless the process is weak
- Antiparticles have opposite numbers and charges

Exercises

- **Determine if the following processes are possible, and if yes, with which interaction:**

$$p + \bar{p} \rightarrow \pi^{+} + \pi^{-} + \pi^{0} + \pi^{+} + \pi^{-}$$

$$p + K^{-} \rightarrow \Sigma^{+} + \pi^{-} + \pi^{+} + \pi^{-} + \pi^{0}$$

$$p \rightarrow \Lambda^{0} + \bar{\Sigma}^{0} + \pi^{+}$$

$$\bar{\nu}_{\mu} + p \rightarrow \mu^{+} + n$$

$$\bar{\nu}_{e} + p \rightarrow e^{+} + \Lambda^{0} + K^{0}$$

$$\Sigma^{0} \rightarrow \Lambda^{0} + \gamma$$