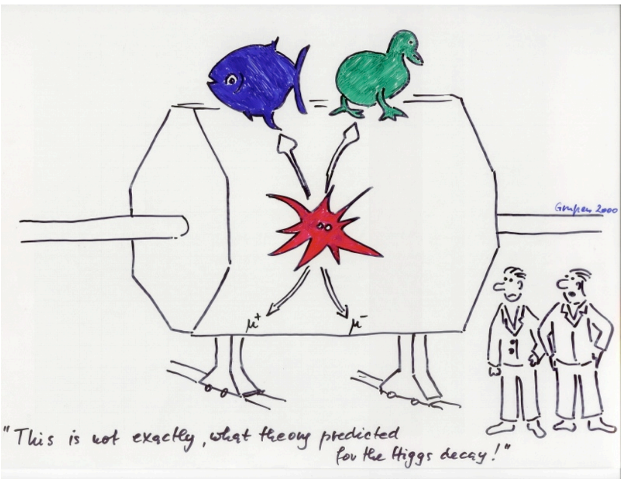
Nuclear and Particle Physics Junior Honours:

Particle Physics

Lectures 10. The Standard Model & Beyond

March 12th 2007



- Neutrinos
- The Higgs
- Supersymmetry
- Unification

The Higgs Mechanism

1. Physicists at a conference reception; all free to move around the room.

2. In comes a noble prize winner; everyone wants to speak to him.

The physicists crowd around him. The noble laureate is not free to move around; he has gained inertia by interacting with the crowd.

This is analogous to how the particles acquire mass: by interacting with the Higgs field. Laureates of different popularity gain different masses.

The Higgs Boson

The next evening; physicists enjoying another drink.

A rumour enters the room: the keynote speaker tomorrow will announce the discovery of a new particle!

The physicists gather together to spread the rumour. The group of physicist acquire inertia.

The clustering of the field of physicists is as if a new massive particle has formed. This is the Higgs boson.

Neutrinos

Pauli hypothesised the neutrino to explain the nuclear beta decay energy spectrum

- $n \rightarrow p\, e^- \bar{\nu}_e$ $\quad p_e = p_n - p_p - p_{\bar{\nu}}$

The recoil of the nucleus is very small ⇒ $E_e \approx m_n c^2 - m_p c^2 - E_{\bar{\nu}}$

Neutrino means "little neutral one". They have:

- no colour charge
- no electric charge
- only interact via the weak force: very small interaction rate.

Pauli: *"I have done a terrible thing. I have postulated a particle that cannot be detected."*

Neutrinos **can** be detected via inverse beta decay *e.g*:

$$\begin{aligned} \nu_e + n &\rightarrow p + e^- \\ \bar{\nu}_e + p &\rightarrow n + e^+ \end{aligned}$$

Tiny cross section:

$$\sigma(\bar{\nu}_e + p \rightarrow n + e^+) \approx 5 \times 10^{-20} \left(\frac{E_{\bar{\nu}}}{\mathrm{MeV}}\right)^2 \mathrm{barn}$$

Mean free path of neutrinos in water is ~60 light years for a 1 MeV anti-neutrino!

Neutrino Sources & Detectors

Where can we find neutrinos?

The Sun

- Standard Solar Model predicts rates and energy spectra for ν_e

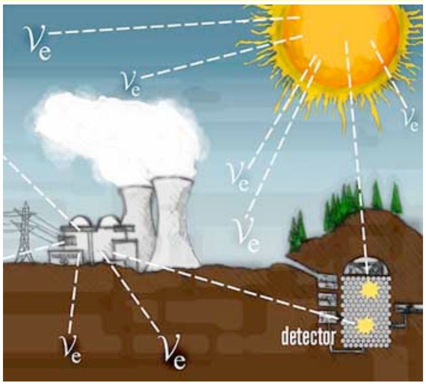
Cosmic rays

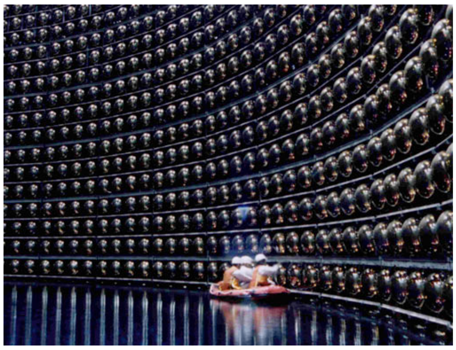
- $\pi^+ \rightarrow \mu\nu_\mu$; $\mu^+ \rightarrow e^+\nu_e\bar{\nu}_\mu$

Nuclear Reactors

Accelerators

- Decay of muons: $\mu^- \rightarrow e^-\bar{\nu}_e\nu_\mu$





To detect neutrinos:

- Get a lot of stuff
  e.g. water, cleaning fluid, steel...
- Leave in a area of neutrino flux
- Be patient.

Solar Neutrinos

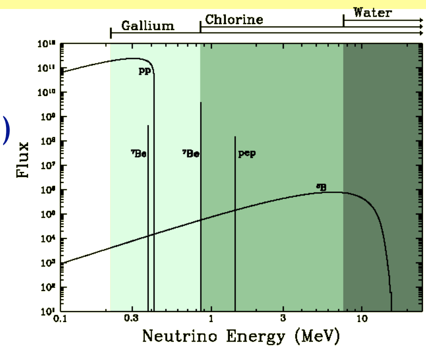
Solar neutrinos were first detected during the 1970s in the Homestake mine, South Dakota

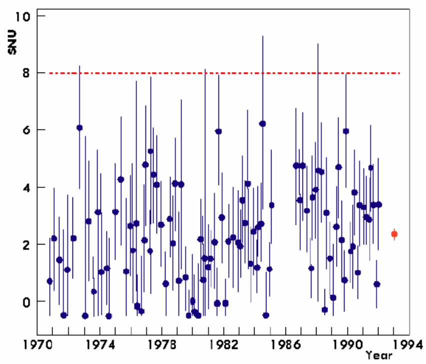
- 100,000 gallons of C_2Cl_4 (dry cleaning fluid)

$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow e^- + {}^{37}\mathrm{Ar}$$

Expectation: 1.5 Ar atoms/day produced

- Only 0.5 Ar atoms/day found





Either:

- the Standard Solar Model is wrong
- we don't know the cross section for neutrino scattering
- electron neutrinos are going missing between the sun and the earth ←

Noble prize in 2002 for Ray Davis Jr.

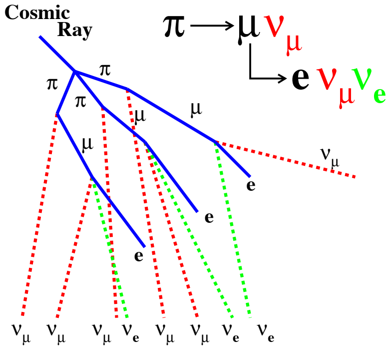
Atmospheric Neutrinos

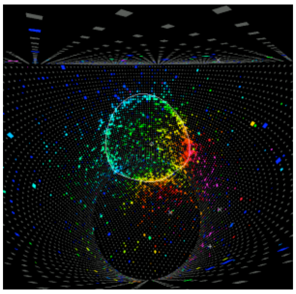
Super-Kamiokande detects atmospheric neutrinos.

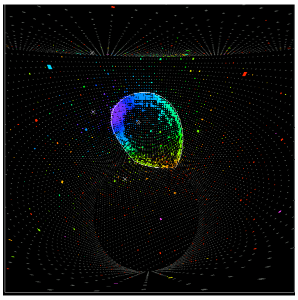
$$\nu_e + N \rightarrow e^- + X$$

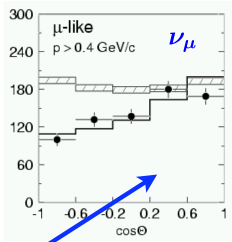
$$\nu_\mu + N \rightarrow \mu^- + X$$

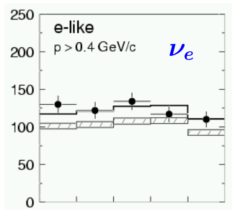
The electron or muon travels through the water with $v(e,\mu) > v_{water}$: Čerenkov radiation is emitted.











As most neutrinos don't interact, neutrinos produced all around the globe can be detected.

Observed: deficit of ν_μ from other side of earth.

- Interpreted as $\nu_\mu \rightarrow \nu_\tau$ OSCILLATIONS in the earth's crust.
- The different flavours of neutrinos mix and neutrinos have mass!

Neutrino Masses

Both solar and atmospheric neutrino experiments provide evidence for neutrinos changing flavour as they travel.

(*i.e.* L_e, L_μ, L_τ not perfectly conserved!

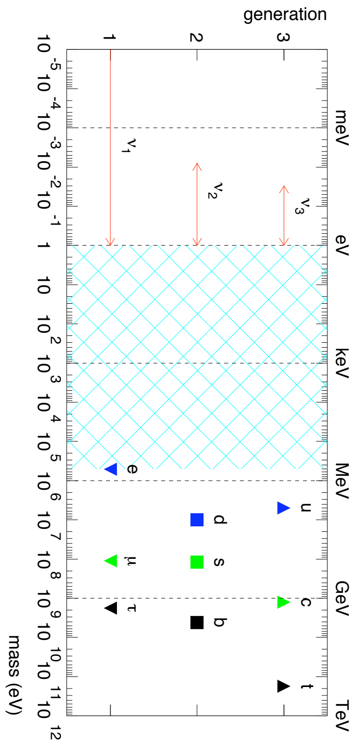
Net number of leptons ***is*** conversed.)

Neutrino flavour change is only possible if neutrinos have mass!

- Neutrino masses are not allowed in the Standard Model

Many experiments now underway with accelerator and reactor neutrinos. → Our understanding of neutrinos is rapidly evolving!

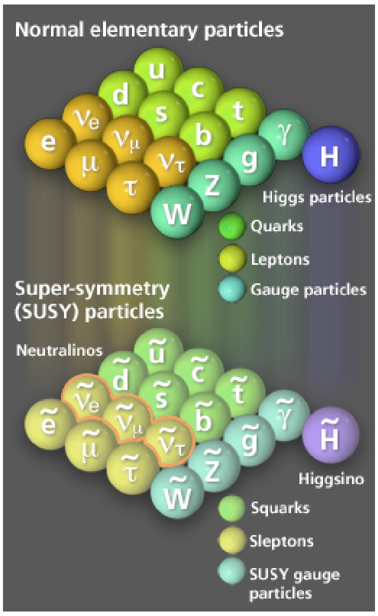
Neutrino masses provided the first evidence for particles physics beyond the Standard Model.



Supersymmetry

Particle physicists are hard to please...

Some of us would like extra fundamental particles, related to the observed particles by **supersymmetry**



Supersymmetry is symmetry between fermions and bosons:

- Every fundamental fermion has a boson partner. *e.g.:*

  $u \leftrightarrow \tilde{u}$ — up-quark ↔ up squark

  $\tau \leftrightarrow \tilde{\tau}$ — tau-lepton ↔ tau-slepton

- Every boson (*W*, *Z*, γ, Higgs) has a fermion partner *e.g.:*

  $W \leftrightarrow \tilde{W}$ — W-boson ↔ Wino

  $H \leftrightarrow \tilde{H}$ — Higgs ↔ Higgsino

Unification of the Forces

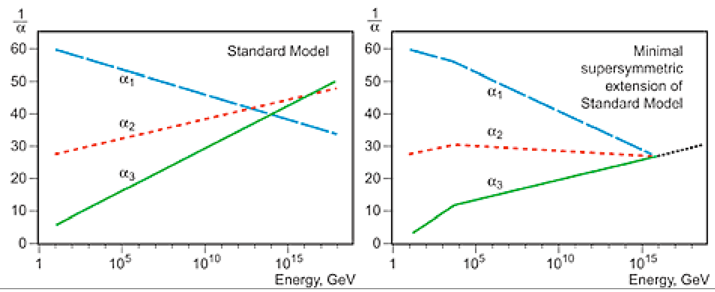
Maxwell equations' show that electric and magnetic interactions are manifestations of one interaction: **electromagnetism**.

We now know the electromagnetic and weak interactions are manifestations of one underlying interaction: **the electroweak interaction**.

- We have to look at high energies, $E \sim O(m_Z, m_W)$ to see most of the consequences of this unification.

The couplings of the electromagnetic, weak and strong interactions change as a function of energy.

- Maybe the electroweak and strong forces are a manifestation of a unified force? This would only become apparent at higher energies.
- Our current measurements tell us that, without new particles, the coupling constants won't become equal.... Suggests new particles ??



And what about gravity?

The ultimate unification of the forces should include gravity.

- But gravity is very much weaker than the other forces...

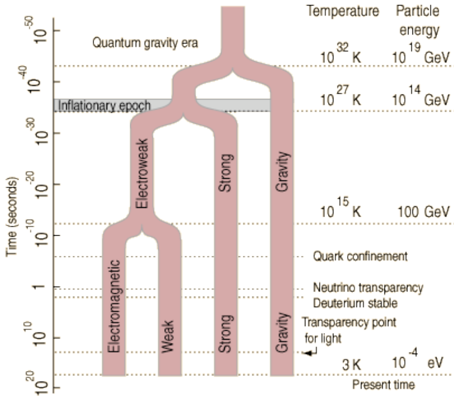
Many ideas proposed to explain this.

e.g. **Extra dimensions**

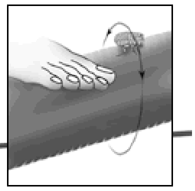
- Most particles (and us) can only travel in the regular 3 space + 1 time dimensions
- Gravitions - the bosons which propagate gravity - can travel in the extra dimensions.
- Strength of gravity is natural weaker in our dimensions

$$F(r) = G\frac{m_1 m_2}{r^2} \rightarrow G_{\rm new}\frac{m_1 m_2}{r^4}$$

- They have to be small extra dimensions, otherwise we'd have seen them already.
- If the dimensions are big enough we might see their effects at the LHC!



Speculative!



Summary

<table>
<tr><td colspan="2">The Standard Model is a beautiful theory of (almost) all the measurements we see in particle physics.... But it isn't the whole picture.</td><td>"We can explain everything, but we understand (at a fundamental level) almost nothing!"</td></tr>
<tr><td>The Higgs mechanism explains the masses of the fermions and massive bosons.</td><td>Neutrinos flavours mix: $\nu_e \leftrightarrow \nu_\mu \leftrightarrow \nu_\tau$
Only possible if neutrinos have mass!</td><td>Supersymmetry is one popular theory for physics beyond the Standard Model.</td></tr>
<tr><td colspan="2">Ultimately we think the electroweak, strong and gravitational forces should be described by one underlying interaction.</td><td>Lots of fun to come!</td></tr>
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