PC4521 - Frontiers of Particle Physics - Lectures 5&6

Number of generations

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \cdots$$

$$\begin{pmatrix} e \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau \\ \nu_\tau \end{pmatrix} \cdots$$

$e^+e^- \to Z^0$

Possible decays of the Z^0 are to all of leptons, quarks and neutrinos:

$$Z^0 \to \ell^+\ell^-$$

$$Z^0 \to q\bar{q}$$

$$Z^0 \to \nu\bar{\nu}$$

$$Z^0 \to \underbrace{\ell^+\ell^-}_{\substack{e^+e^- \\ \mu^+\mu^- \\ \tau^+\tau^-}} + q\bar{q} + \nu\bar{\nu}$$

Neutrinos are invisible. Can be $\nu_e\bar{\nu}_e + \nu_\mu\bar{\nu}_\mu + \nu_\tau\bar{\nu}_\tau$. Lepton universality says that σ for the decay to each pair is the same.

We know the number of Z^0 produced $\left(L, \sigma_{e^+e^- \to Z^0}\right)$. Can count the number that go to leptons and quarks, so the remainder must be leptons.

Plot σ vs. the energy. There will be a large bump in the cross-section. This will give you a fit for the number of leptons that exist, which shows that there are only three neutrino types ($= 2.994 \pm 0.012$)

This is an indirect method of doing this – we're not measuring the neutrinos, just deducing them. It would be better to count the number of neutrino's, but as they have a very low cross-section this is rather difficult to do…

ISR – Initial State Radiation – can take place (electron and positron attracting each other before they collide, and one of them giving off a real photon. After this, they must collide), and can be counted in the collider. This is a signal that the Z^0 has been produced; it is only if there is no other particles in the detector that you know there was a neutrino. Can hence count the number of neutrinos – which gives the number of neutrino types to be 2.92 ± 0.07.

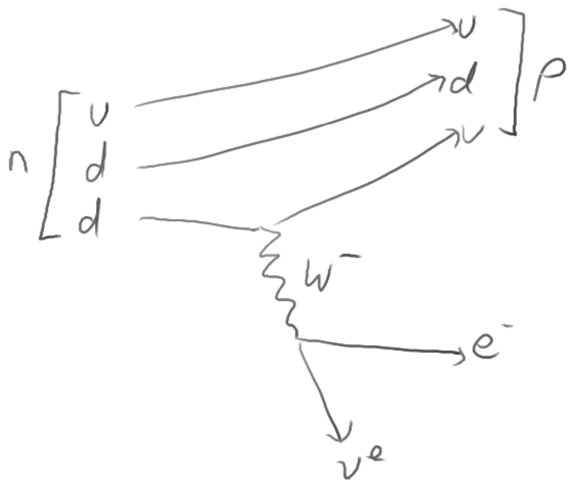
We say that there are no more "normal" neutrinos, i.e. with mass $< \frac{m_{Z^0}}{2}$, and normal neutrino interaction coupling (e.g. it could have a very low cross-section). This would mean that there is no more quarks, even if they have mass $> \frac{m_{Z^0}}{2}$ (assuming that the quark/lepton families are symmetric).

W Boson

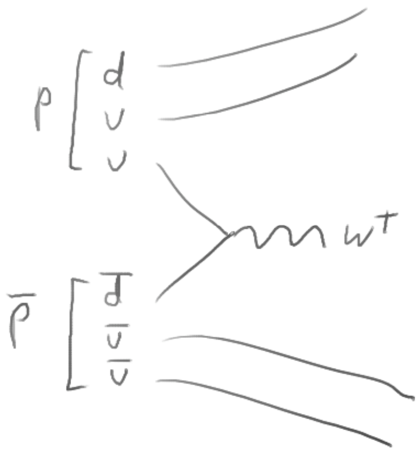
$W^\pm$ has a mass $\sim 80GeV$, and couples to both quarks and leptons.

In the same way that early $e^+e^- \to \mu^+\mu^-$ asymmetry led to predictions of the (virtual) Z^0 at energies much less than m_{Z^0}, β decay should go via a $W^\pm$.

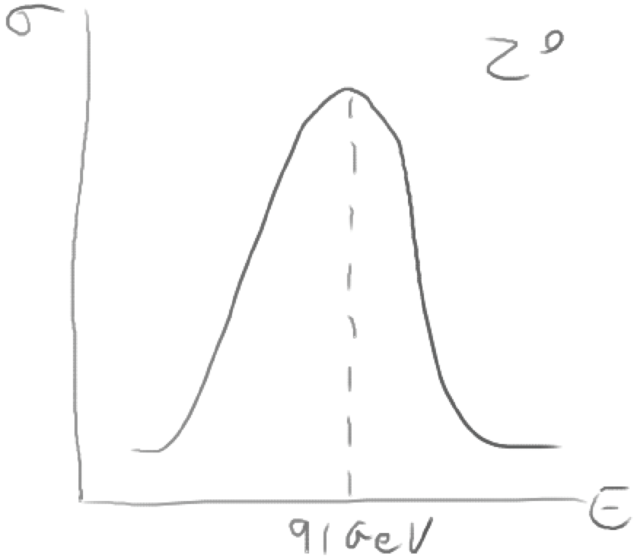
$n \to pe\overline{\nu}_e$



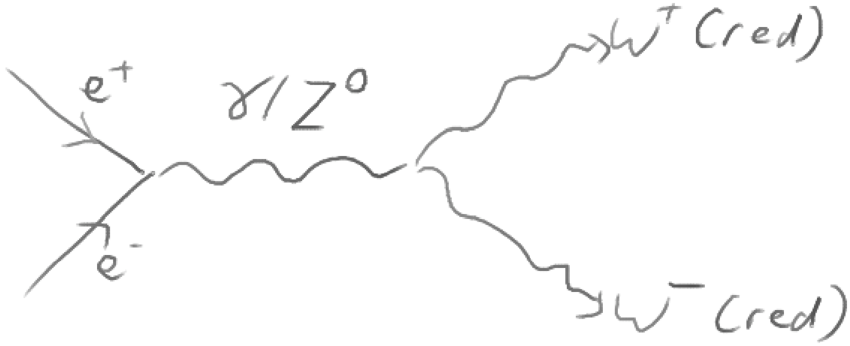
W^+ discovered in $\overline{p}p$.



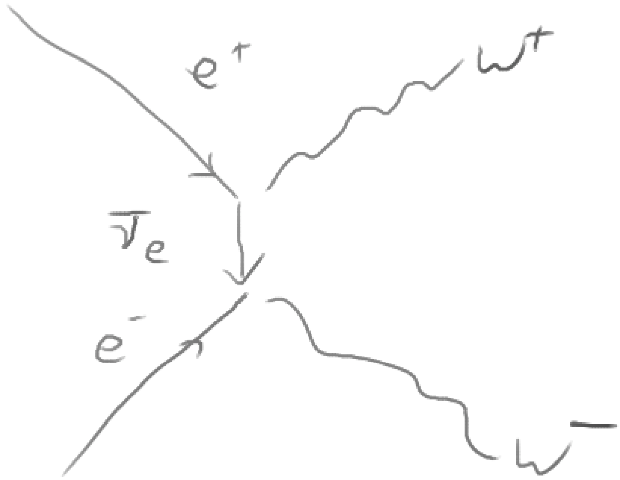
The nice thing with Z^0 at LEP was that it went through $e^+e^- \to Z^0$, which generates a real single Z^0 at rest. Hence the cross-section is like:

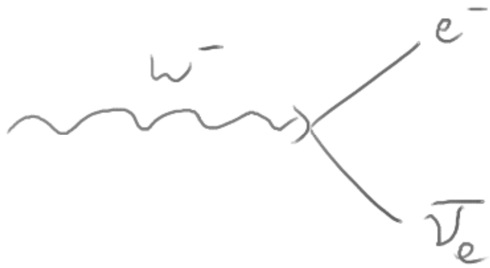


However, $W^{\pm}$ are charged hence they must be produced in a pair.

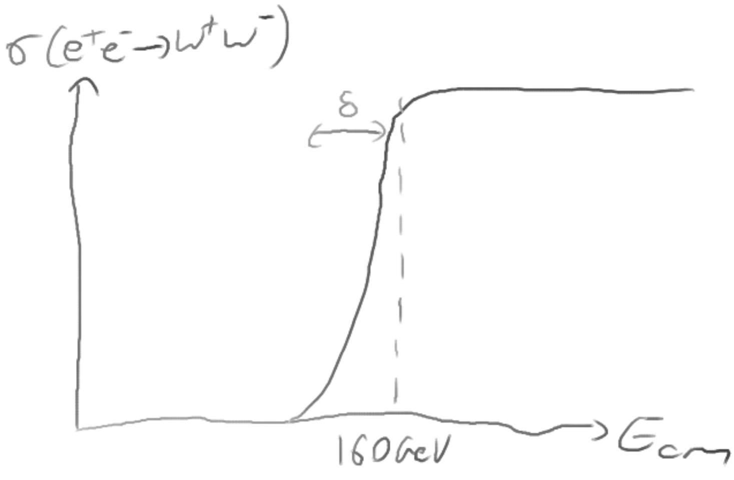


Hence $E_{CM} \geq 2M_W$ i.e. $\geq 160GeV$ → LEP2 (≥ 1996).
There is also another process which happens:





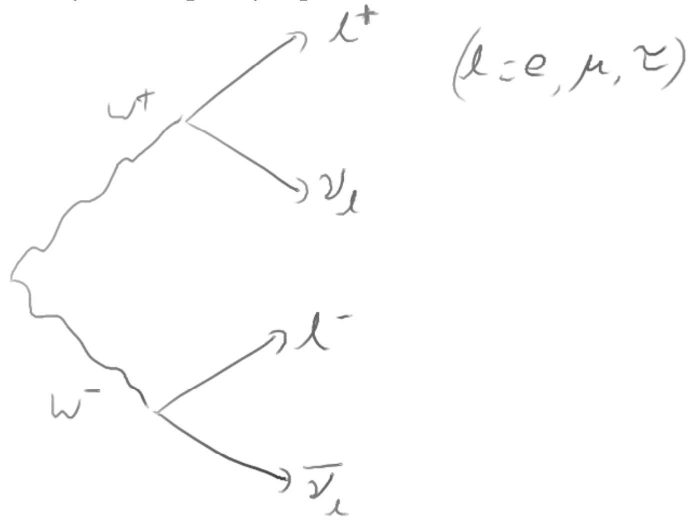
There is no way of differentiating between these two processes – you just see the combination of the two processes, and any interference between them which might exist as a result of quantum mechanics.



δ : uncertainty width.
After the threshold energy of $160 GeV$, extra energy can go into kinetic energy as there are two particles (KE equally and opposite).

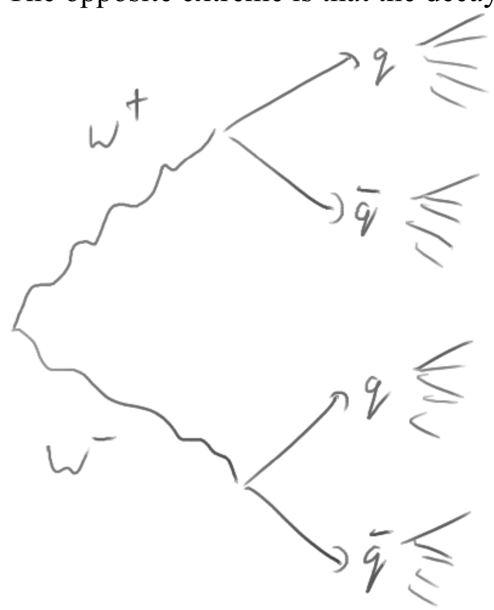
$W^{\pm}$ decay and detection

$\tau_W \sim 10^{-25} s$, so we don't actually ever see a W - by the time we attempt to measure it, it's decayed.
Decay can be purely leptonic.



This has the advantage that it is very clean – there are only two particles which come out which need to be detected. The ℓ^+ and ℓ^- are easy to detect and identify. The disadvantage is that half the event is invisible. We don't see either of the neutrino's – this is a major problem.

The opposite extreme is that the decay can be purely hadronic.



Quarks hadronise into jets. This has the advantage that all produced decay products are detectable, however it has the big disadvantage that you get a "hell of a mess" – lots of particles, which tend to overlap and confuse their origins.

The compromise is that the decay can be semi-leptonic.

Identify particles to jets, and measure the invariant mass of the di-jet system. This should be the mass of the W^+. The lepton is easy to detect, and the neutrino can be deduced through missing momentum and energy. Can hence reconstruct the W^-. Combined with the W^+, we can measure all of the components of the interaction.

$M_W = 80.419 \pm 0.056 GeV$

$\Gamma_W = 2.12 \pm 0.05 GeV$ (natural width, from Heisenberg uncertainty)

Higgs Boson

How do particle acquire their mass? The simplest standard model has the mass of the $Z^0, W^\pm = 0$. Need to incorporate a theory whereby the particles acquire mass by interaction with a field (Higgs field). The field is present always in the absence of any specific charge. [EM field needs electric charge, strong field needed colour charge, gravity needs mass]

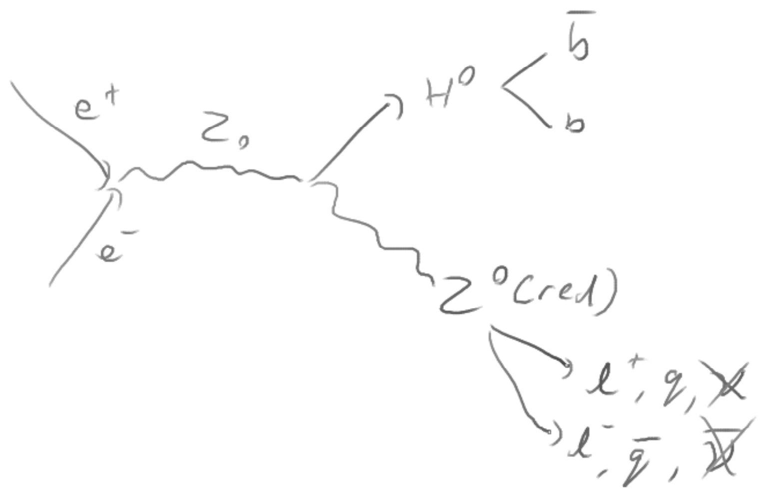
(Most people aren't worried that this seems very like the old Aether theory…)

[Is this field invariant through all space? Do particles have a reciprocal effect on it?]

Fields in general always have associated with them interaction bosons – e.g. the Gluon, Photon, W and Z - all spin 1.

Higgs Field → Higgs Boson with spin 0 (there is at least one neutral, maybe more charged). We expect H^0 to be real and detectable.

We know that H^0 will interact most strongly with the most massive particles. So the decay of H^0 will be dominated by the production of the heaviest (kinematically) possible decay products.



$b\bar{b}$ is the heaviest decay route possible.
Identify the Z^0 decay, and measure them.
Reconstruct the b-jets then look for the invariant mass of the di-jet, which should give a constant value equal to the mass of the Higgs boson.

By January 2000, this had been searched for and not seen. This puts a lower limit of $M_{H^0} > 95GeV$.
Theoretical predictions (MSSM – Minimal Supersymmetric Standard Model) were $M_{H^0} = \left(122^{+134}_{-77}\right)GeV$.
LEP run up to maximum – it was going to be dismantled shortly, so it didn't matter if this broke it.
September 2000 – a few candidate events were found at $M_{H^0} = 115GeV$.
LEP was extended until November 2000 – 19 events found.
4 experiments – ALEPH (5), DELPHI (5), L3 (4), OPAL (5), so events were uniformly distributed around the experiments.
Topologies were:
9 x Hqq
4 x $H\ell^+\ell^-$
6 x $H_{\nu\bar{\nu}}$
All gave $M_H = 115^{+0.7}_{-0.3}GeV$. 2.9σ signal – an indication rather than a discovery (which needs around 5σ).

Tevatron ($p\bar{p}$, E_{cm} of $2TeV$) has found no evidence for the Higgs, but the cros-section for it is very low at this machine. If it is not found by 2007, this will put the limit $M_H \geq 130GeV$.
2007 – LHC with pp $E_{cm} = 14TeV$ will come online.