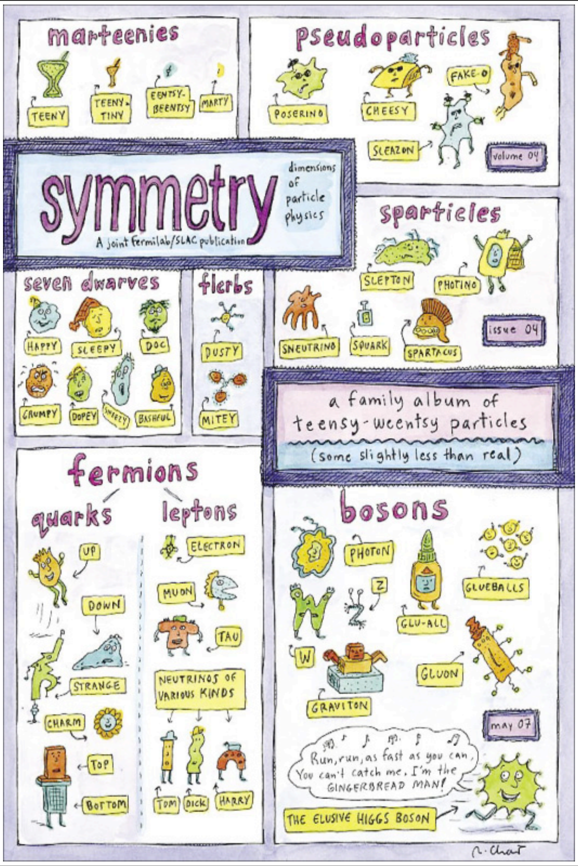


Physics 3:
Particle Physics

Lecture 9: Electroweak Model and the Higgs boson

March 10th 2008

- Electroweak Theory
- Interactions of W and Z bosons at high energy
- The Higgs boson

Electroweak Theory

We've seen already that wherever a γ boson can be exchanged a Z can also be exchanged:

- The weak and electromagnetic force are linked.
- At short distances (or high energies) the strength of the electromagnetic force and the weak force are comparable. Can be related by a parameter, $\sin\theta_W$

$$e = g_W \sin\theta_W$$

The weak and electromagnetic interactions are manifestations of a underlying force: **the electroweak force.**

- Couplings of the γ, W (and Z) bosons are related: $e = g_W \sin\theta_W$
- Mass of the W and Z bosons are related: $m_Z^2 = m_W^2/\cos^2\theta_W$

Just three fundamental parameters required to describe:

- couplings of W, Z and γ to quarks and leptons
- masses of the W, Z, γ bosons
- interactions of the W, Z, γ bosons with each other

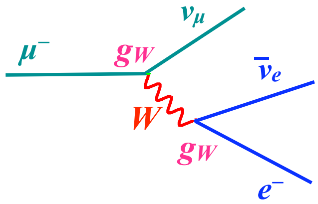
Normally use three most accurately measured parameters e.g. e, G_F, m_Z

W and *Z* boson at low energies

At low energies, $\underline{\underline{q}} \ll m_Z, m_W$:

- The *W* and *Z* bosons are virtual:

$$\begin{aligned} \underline{\underline{q}}_Z^2 &= E_Z^2 - \vec{p}_Z \cdot \vec{p}_Z \neq m_Z^2 \\ \underline{\underline{q}}_W^2 &= E_W^2 - \vec{p}_W \cdot \vec{p}_W \neq m_W^2 \end{aligned}$$

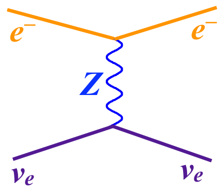


$\mu^- \to e^- \bar{\nu}_e \nu_\mu$

$\underline{\underline{q}}_W^2 \neq m_W^2$

- virtual *W*-bosons are responsible for the decays of the leptons, and the lightest hadrons *e.g.* $\mu^- \to e^- \bar{\nu}_e \nu_\mu$

- interactions of virtual *Z*-boson are not clearly evident, as they look similar to γ interactions (γ interactions are much stronger than *Z*-boson interactions)



$\nu_e e^- \to \nu_e e^-$

$\underline{\underline{q}}_Z^2 \neq m_Z^2$

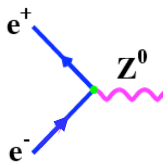
At low energies we see the effect of *Z* boson mainly in scattering involving neutrinos *e.g.* $\nu_e e^- \to \nu_e e^-$

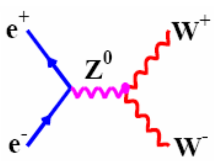
- as γ cannot couple to the neutral neutrinos

W and *Z* boson at high energies

Using a collider, we can create high enough energies to make real *W* and *Z* bosons:

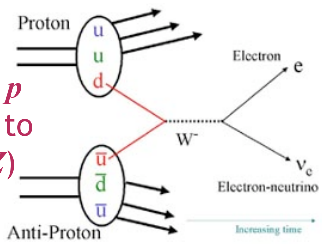
$$\underline{\underline{q}} \sim m_Z, m_W$$





- e.g. LEP collider $e^+e^- \to Z$, $e^+e^- \to W^+W^-$
- e.g. Tevatron and Sp$\bar{\text{p}}$S collider $p\bar{p} \to Z + X$, $p\bar{p} \to W + X$

quarks within p and $\bar{p}$ interact to make *W* (or *Z*)



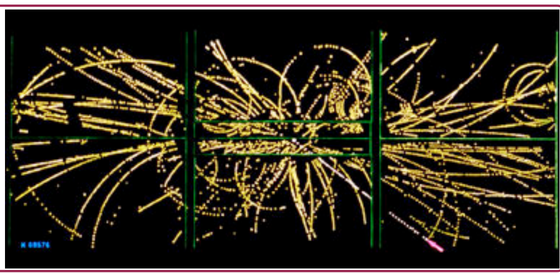
Can study the properties of the *W* and *Z* bosons in detail.

- masses, lifetime/width, coupling strengths, decay modes, spin...

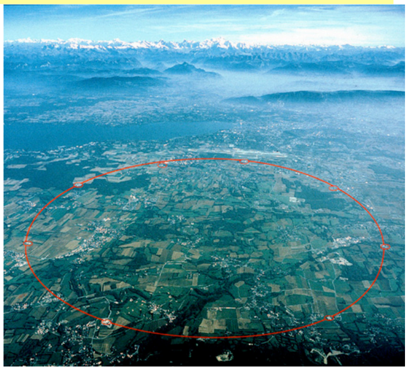
Discovery of *W* and *Z* bosons at CERN in 1983 at the Sp$\bar{\text{p}}$S collider.

$E_p = E_{\bar{p}} = 270$ GeV

$p\bar{p} \to W^- \to e^-\bar{\nu}_e$ event at UA1 experiment



W and *Z* boson tests at LEP



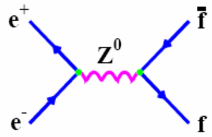
LEP - the Large Electron Positron Collider at CERN

The world's highest energy e^+e^- collider:

- 27 km circumference, ran from 1989 to 2000
- Energy of mass energy, $\sqrt{s} = 89$ to 206 GeV
- Four experiments: Aleph, Delphi, L3, Opal
- Measurements corroborates unification of EM & Weak forces

***Z*-boson production**

- ~4 million $e^+e^-\rightarrow Z^0$ events

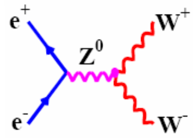


$\sqrt{s} \sim 91$ **GeV**

$$s = (\underset{=}{q}_{e^+} + \underset{=}{q}_{e^-})^2 = \underset{=}{q}_Z^2 = m_Z^2$$

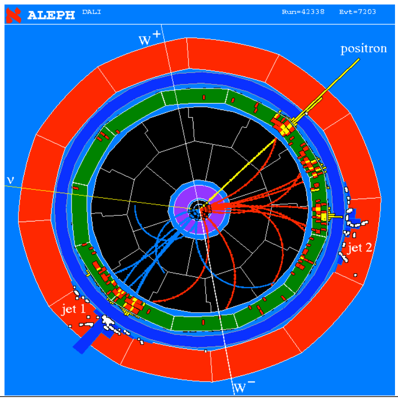
***W*-boson production**

- ~8000 $e^+e^-\rightarrow Z\rightarrow W^+W^-$ events



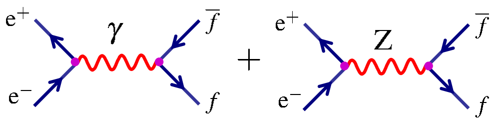
$\sqrt{s} \sim 160$ **GeV**

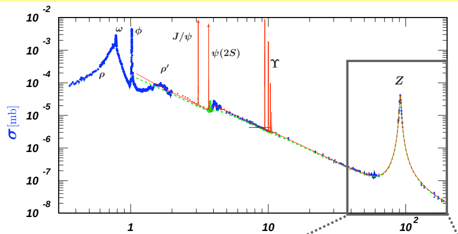
$$s = (\underset{=}{q}_{e^+} + \underset{=}{q}_{e^-})^2 = (2m_W)^2$$



*Z*⁰ resonance

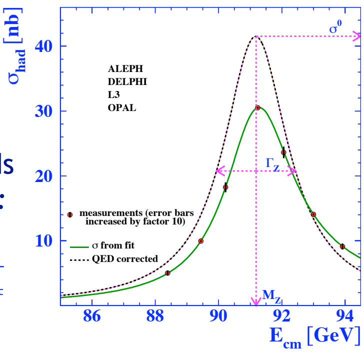
- Both γ and Z contribute to $e^+e^-\rightarrow$**hadrons**

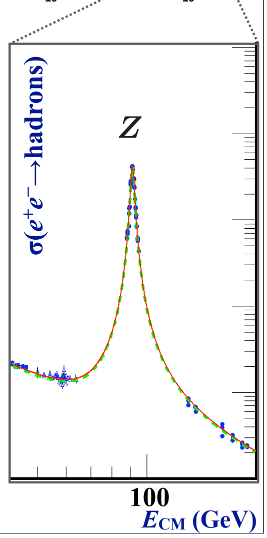




- At low E_{CM} mainly γ interactions
- At $\sqrt{s}\sim m_Z$, mainly Z-boson:

$$\sigma(e^+e^- \rightarrow Z \rightarrow f\bar{f}) \propto \frac{1}{(\underset{=}{q}^2 - m_Z^2)^2}$$





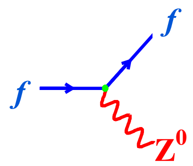
- For a massive boson, $\mathcal{M}$ also depends on total width $\Gamma_Z = \hbar/\tau_Z$. Shape of σ:

$$\sigma(E = \underset{=}{q}^2) = \sigma_{\max}\frac{\Gamma_Z^2/4}{(\underset{=}{q}^2 - m_Z)^2 + \Gamma_Z^2/4}$$

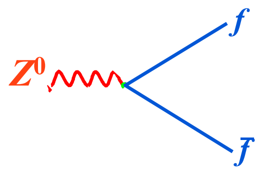
- Measurements at LEP:
  - $m_Z = 91.188 \pm 0.002$ **GeV/c²**
  - $\Gamma_Z = 2.4953 \pm 0.002$ **GeV**

Decays of the Z boson

Z boson interacts with **all** quarks and leptons.
No change of quark or lepton flavour at Z boson vertex.



- Z boson can decay into any pair: fermion–anti-fermion, $f\bar{f}$.
- except top quark pair, as $m_Z < 2m_t$



$Z\to e^+e^-$	$Z\to\nu_e\bar{\nu}_e$	$Z\to u\bar{u}$	$Z\to d\bar{d}$
$Z\to\mu^+\mu^-$	$Z\to\nu_\mu\bar{\nu}_\mu$	$Z\to c\bar{c}$	$Z\to s\bar{s}$
$Z\to\tau^+\tau^-$	$Z\to\nu_\tau\bar{\nu}_\tau$		$Z\to b\bar{b}$

Lepton Universality $\Rightarrow$

- $\mathcal{M}$ for e, μ, τ decay is same $\Rightarrow \Gamma(Z\to e^+e^-) \approx \Gamma(Z\to\mu^+\mu^-) \approx \Gamma(Z\to\tau^+\tau^-)$
- $\mathcal{M}$ for ν_e, ν_μ, ν_τ decay is same $\Rightarrow \Gamma(Z\to\nu_e\bar{\nu}_e) = \Gamma(Z\to\nu_\mu\bar{\nu}_\mu) = \Gamma(Z\to\nu_\tau\bar{\nu}_\tau)$

Number of Neutrinos

Total width of the Z-boson (Γ_Z) is sum of all partial widths:

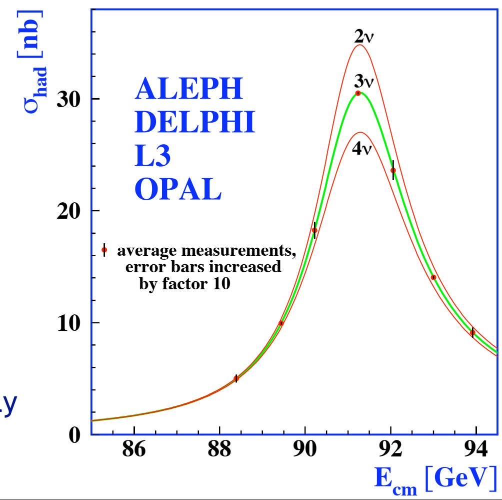
$$\Gamma_Z = \Gamma(Z\to q\bar{q}) + \Gamma(Z\to e^+e^-) + \Gamma(Z\to\mu^+\mu^-) + \Gamma(Z\to\tau^+\tau^-) + N_\nu\,\Gamma(Z\to\nu\bar{\nu})$$

LEP directly measured:

- partial widths: $\Gamma(Z\to e^+e^-)$, $\Gamma(Z\to\mu^+\mu^-)$, $\Gamma(Z\to\tau^+\tau^-)$, $\Gamma(Z\to\text{hadrons}) = \Gamma(Z\to q\bar{q})$
- total width, Γ_Z

Cannot measure $\Gamma(Z\to\nu\bar{\nu})$ directly as neutrinos leave no signal in the detector.

- Can predict $\Gamma(Z\to\nu\bar{\nu})$ using $\mathcal{M}(Z\to\nu\bar{\nu})$
- Use prediction & measurements to find number of neutrinos contributing to Γ_Z
- $N_\nu = 2.999 \pm 0.011$



Consistent with exactly three neutrinos!

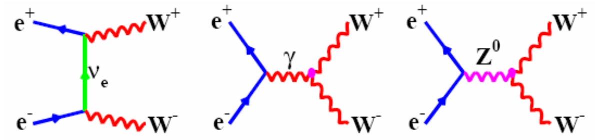
$\Rightarrow$ Gives us confidence that there are exactly three generations of quarks and leptons

W-boson

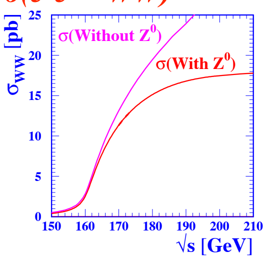
Colliders may also produce W-bosons ⇒ measure properties of the W-boson

At LEP: W-bosons produced in pairs

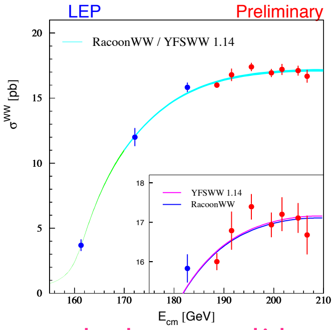
Three possible modes:



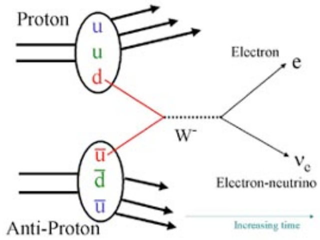
Predicted $\sigma(e^+e^- \to WW)$



$\sigma(e^+e^- \to WW)$ measured at LEP confirms Z^0-W^+-W^- vertex



At Tevatron: W-bosons produced from quarks and anti-quarks in $p\bar{p}$



From measurements at LEP & Tevatron:

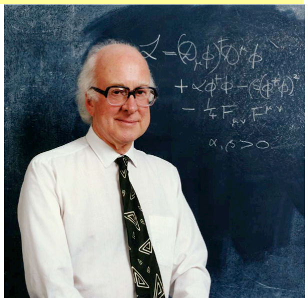
- $m_W = 80.413 \pm 0.048$ GeV/c^2
- $\Gamma_W = 2.141 \pm 0.041$ GeV

Measurements of W and Z bosons validate the Electroweak Model beautifully

The Higgs Boson

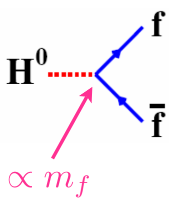
The Higgs boson: missing piece of the Standard Model.

- The theoretical framework for the Standard Model only works for massless bosons and massless fermions.
- Introducing Higgs field give masses to the W and Z bosons
- Two key consequences:
  - The fermions also get a mass!
  - The existence of an additional massive, neutral boson: **the Higgs boson**
- Mass of the Higgs is not predicted in Standard Model, we have to search for it.

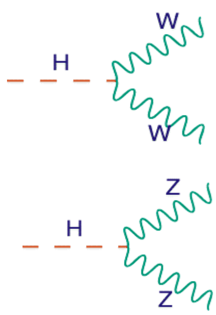


Peter Higgs emeritus professor in the School of Physics

Higgs interacts with W and Z bosons, and all massive fermions.



Interaction strength between Higgs and fermions ∝ fermion mass, m_f



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

3. The next evening; physicists enjoying another drink.

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

4. 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.

The Search for the Higgs

Higgs boson has been searched for at LEP, is being searched for at the Tevatron, will be searched for at LHC.

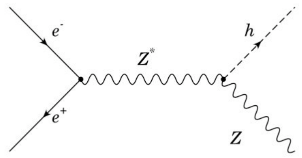
- The Higgs generally likes to decay to the heaviest thing it can.
- m_H < ~135 GeV search for $H \to b\bar{b}$ decay.
- m_H > ~135 GeV search for $H \to W^+W^-$, $H \to Z^0Z^0$ decays. (1 boson may be virtual)

Lots of other processes look like Higgs events, challenge is to separate background events from Higgs events.

LEP searched for $e^+e^- \to Z \to ZH$

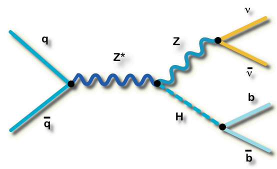
No (conclusive) evidence found

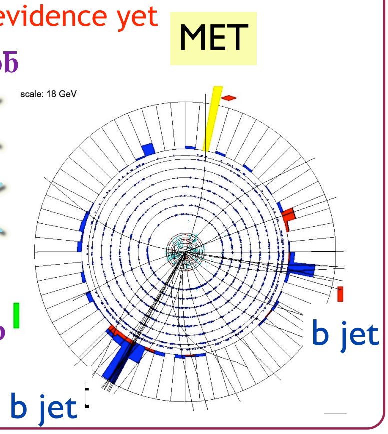
$\Rightarrow m_{Higgs} > 114.4\ \mathrm{GeV}/c^2$



The Tevatron is currently looking for the Higgs boson, no evidence yet

e.g. $p\bar{p} \to Z \to ZH \to \nu\bar{\nu}b\bar{b}$



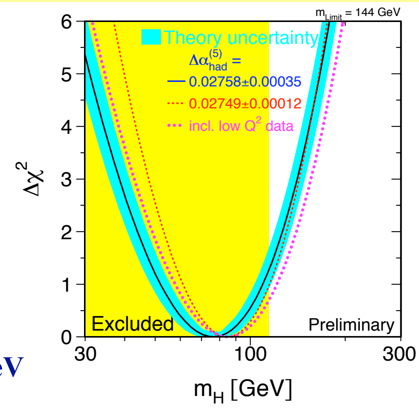


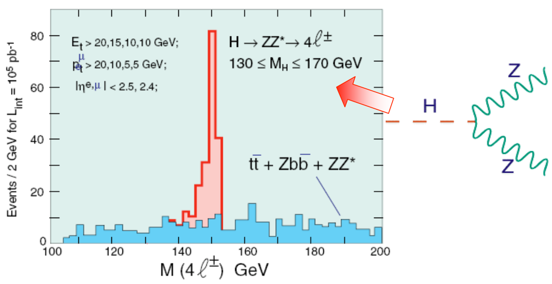
Picture of event in DØ detector which looks like $ZH \to \nu\bar{\nu}bb$ (but could also be background)

Search for the Higgs II

As the Higgs boson can interact with all other bosons and fermions, many measurements are slightly sensitive to Higgs mass.

- Blue band shows the χ^2 of a fit to data as a function of Higgs mass.
- Yellow is LEP excluded region
- Best fit $m_H = 76\ ^{+33}_{-24}$ GeV.
- All evidence suggests that (if the Standard Model is correct) mass of the Higgs is < 200 GeV





Many studies of Higgs bosons searches at LHC made

e.g. $gg \to H \to Z^0Z^0 \to 4$ charged leptons

Using 2 years of data, if $m_H < 1$ TeV the LHC is predicted should find the Higgs.

... otherwise Standard Model is in trouble!

Summary

Electromagnetic & weak are manifestations of a single unified **electroweak interaction.** (just 3 parameters describe interaction!)	**Standard Model** describes electroweak and QCD. Beautifully verified by experiment, apart from missing Higgs boson.
At low energies, virtual W and Z bosons responsible for lepton and lightest hadron decays and neutrino scatterings.	At high energies collider produce real W and Z bosons for study. Studies of Z boson decays suggest that only three generations of quarks and leptons.
Standard Model predicts a Higgs field to account for the masses of the bosons. Higgs field also produces a Higgs boson.	Standard Model makes no prediction for the Higgs boson mass. Searches, as yet, have not found any evidence for the Higgs boson. Should be found at the LHC collider!

Standard Model Interactions

QED	QCD	Weak Neutral Current	Weak Charged Current
quantum theory of EM interactions	quantum theory of strong interactions	quantum theory of weak interactions	
mediated by exchange of virtual photons	mediated by exchange of gluons	mediated by exchange of Z bosons	mediated by exchange of W bosons
acts on all charged particles	acts on quarks only	acts on **all** quarks and leptons	
couples to electric charge	couples to colour charge	does not change quark or lepton flavour	changes quark and leptons flavours
coupling strength $\propto e \propto \sqrt{\alpha}$	coupling strength $\propto g_S \propto \sqrt{\alpha_S}$		coupling strength $\propto g_W \propto \sqrt{\alpha_W}$
propagator: $\frac{1}{q^2}$	propagator: $\frac{1}{q^2}$	propagator: $\frac{1}{(q^2 - m_Z^2)}$	propagator: $\frac{1}{(q^2 - m_W^2)}$