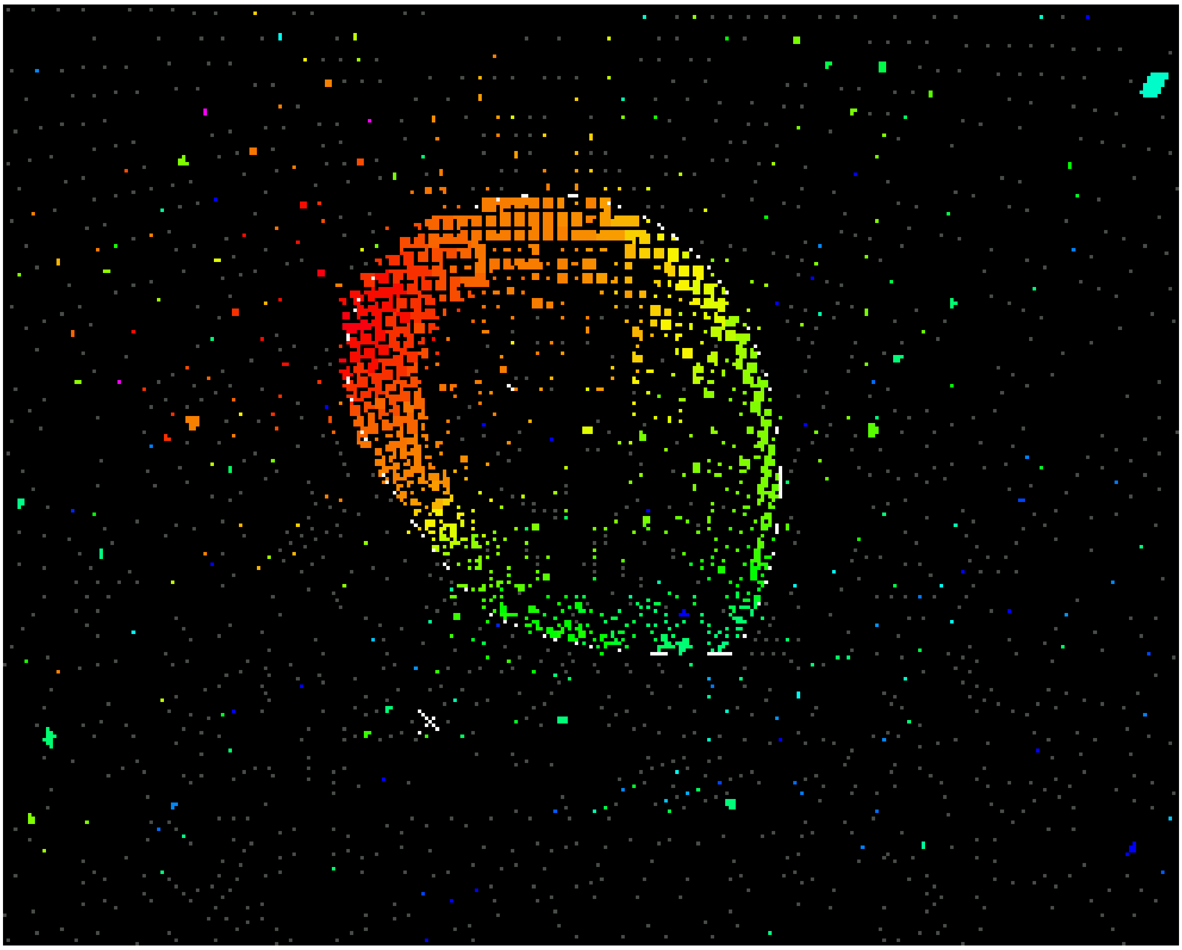
Particle Physics

Dr M.A. Thomson



Part II, Lent Term 2004

HANDOUT VIII

The Standard Model and Beyond

Have precise measurements of the 5 fundamental parameters of the Standard Model governing electroweak unification:

- ★ α_{em}
- ★ $G_{\mathrm{F}} = (1.16632 \pm 0.00002) \times 10^{-5}\ \mathrm{GeV}^{-2}$
- ★ $M_{\mathrm{W}} = (80.426 \pm 0.034)\ \mathrm{GeV}$
- ★ $M_{\mathrm{Z^0}} = (91.1875 \pm 0.0021)\ \mathrm{GeV}$
- ★ $\sin^2\theta_W = 0.23143 \pm 0.00015$

In the Standard Model, ONLY 3 are independent.

Their consistency is an incredibly powerful test of the Standard Model of Electroweak Interactions !

EXAMPLE: M_{W}

In the Standard Model one can predict M_{W} using lowest order perturbation theory:

$$G_\mu = \frac{\pi\alpha_{em}}{\sqrt{2}\sin^2\theta_W}\frac{1}{{M_{\mathrm{W}}}^2}$$

$$\sin^2\theta_W = 1 - \frac{{M_{\mathrm{W}}}^2}{{M_{\mathrm{Z^0}}}^2}$$

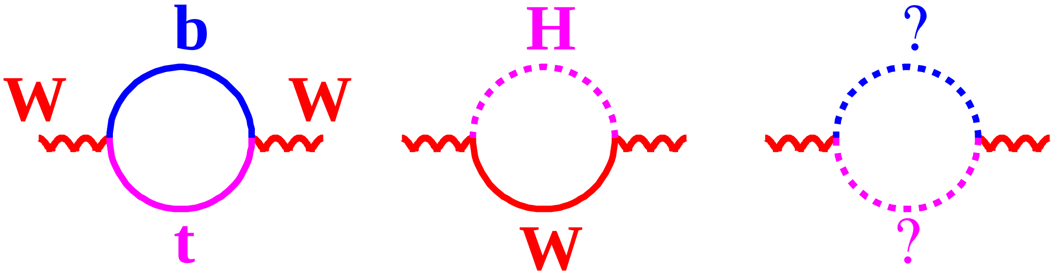
It also provides a window on physics **beyond the Standard Model**

Compare lowest order prediction of $M_W(\alpha_{em}, M_{Z^0}, G_F)$ with measurement:

★ PREDICT $M_W = 80.937\,\mathrm{GeV}$

★ MEASURE $M_W = 80.426 \pm 0.034\,\mathrm{GeV}$

- Lowest order prediction is inconsistent with the measurement
- Need to include higher order diagrams - radiative corrections !



M^2_{top} $\ln(m_H)$?

$$M_W{}^2 \sin^2\theta_W = \frac{\pi\alpha_{em}}{\sqrt{2}G_\mu}(1+\Delta r)$$

where $$\Delta r = AM^2_{top} + B\ln(m_H)$$

and where A and B are calculable constants.

By making precise measurements we are sensitive to particles which are not being produced directly - thus placing constraints on possible new particles/physics beyond the Standard Model.

For example:

★ In 1994 precise measurements gave a prediction of the (then undiscovered) top-quark mass:
$M^{\mathrm{pred}}_{top} = 175 \pm 20$ GeV

★ Later in 1994 it was discovered:
$M_{top} = 174.1 \pm 5.4$ GeV

The Top Quark

leptons Charge

$$\begin{pmatrix} e^- \\ \nu_e \end{pmatrix} \begin{pmatrix} \mu^- \\ \nu_\mu \end{pmatrix} \begin{pmatrix} \tau^- \\ \nu_\tau \end{pmatrix} \qquad \begin{matrix} -1 \\ 0 \end{matrix}$$

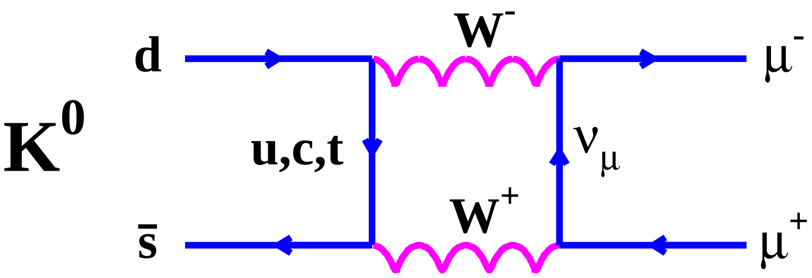
quarks e.g. proton (uud)

$$\begin{pmatrix} u \\ d \end{pmatrix} \begin{pmatrix} c \\ s \end{pmatrix} \begin{pmatrix} t \\ b \end{pmatrix} \qquad \begin{matrix} +\frac{2}{3} \\ -\frac{1}{3} \end{matrix}$$

+ anti-particles

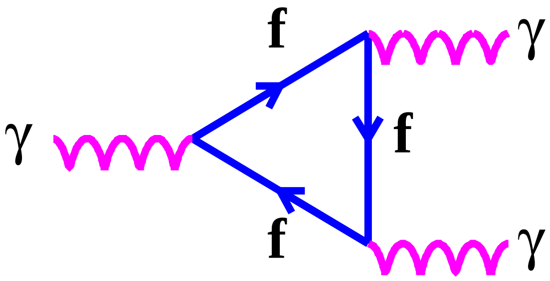
The existence of the TOP QUARK is predicted by the Standard Model and is required to explain a number of observations:

Example: absence of the decay $K^0 \rightarrow \mu^+\mu^-$



In the Standard Model the top quark cancels the contributions from the u and c quarks

Example: Electro-magnetic anomalies



This triangle diagram leads to infinities in the theory unless

$$\sum_f Q_f = 0$$

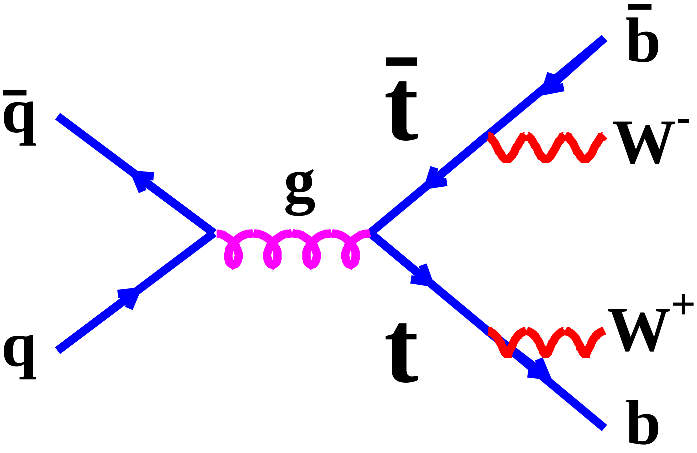
where the sum is over all fermions (and colours)

$$\sum_f Q_f = [3 \times (-1)] + [3 \times 0] + [3 \times 3 \times \tfrac{2}{3}] + [3 \times 3 \times (-\tfrac{1}{3})] = 0$$

The Top Quark

Discovery of the Top Quark

The top quark was discovered in 1994 by CDF and D0 experiments at the world's highest energy $p\bar{p}$ collider, the Tevatron at FERMILAB, U.S.

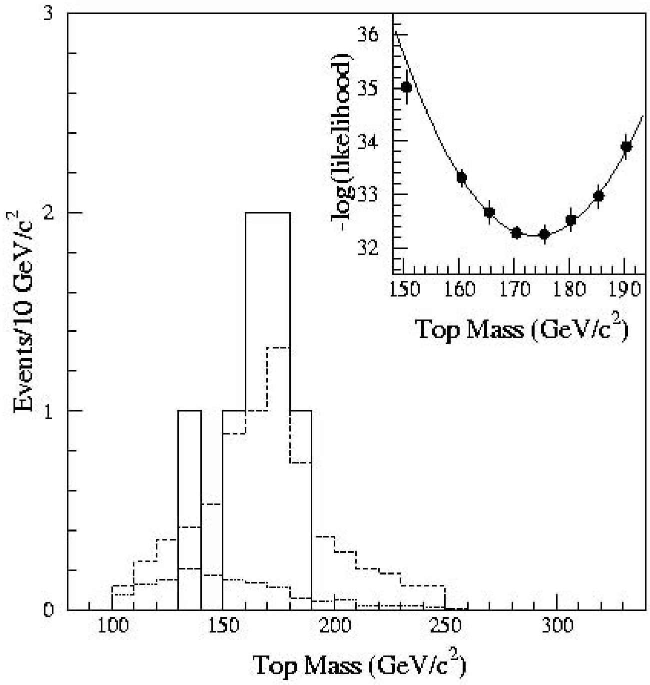


Final State

$W^+W^-b\bar{b}$

(top lifetime too short to allow formation of bound state analogous to J/ψ or Υ)

Mass reconstructed in a similar manner to W-mass at LEP, *i.e.* measure jet/lepton energies/momenta.



$m_{top} = 174$ **GeV**

Open question: Why is m_{top} so much larger than the other fermions ?

The Standard Model c. 1998

MATTER: Point-like spin-$\frac{1}{2}$ Dirac fermions.

Fermion		charge	Mass
Electron	e^-	-1	0.511 MeV
Electron Neutrino	ν_e	0	0 ?
Down quark	d	-1/3	0.35 GeV
Up quark	u	+2/3	0.35 GeV
Muon	μ^-	-1	0.106 GeV
Muon Neutrino	ν_μ	0	0 ?
Strange quark	s	-1/3	0.5 GeV
Charm quark	c	+2/3	1.5 GeV
Tau	τ^-	-1	1.8 GeV
Tau Neutrino	ν_τ	0	0 ?
Bottom quark	b	-1/3	4.5 GeV
Top quark	t	+2/3	174 GeV

and ANTI-PARTICLES

FORCES: Mediated by spin-1 bosons

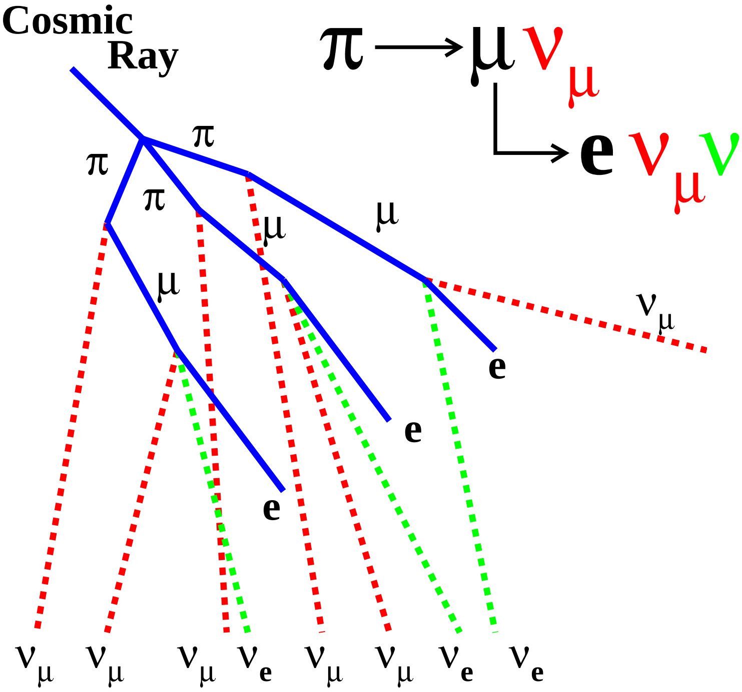
Force	Particle/s	Mass
Electro-magnetic	Photon	0
Strong	8 Gluons	0
Weak (CC)	$\mathrm{W}^{\pm}$	80.4 GeV
Weak (NC)	Z^0	91.2 GeV

- ★ ALL above particles observed (and no others)
- ★ ALL solid experimental observations well described by the above particle and forces, with the exception of one...

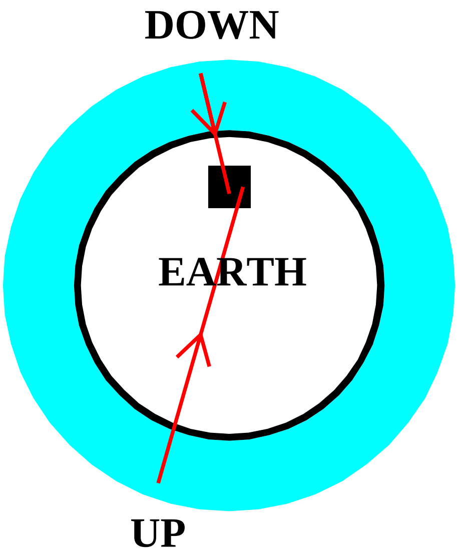
ν-Oscillations $\Rightarrow$ neutrinos have mass

Atmospheric Neutrino Oscillations

In 1998 the Super-Kamiokande experiment announced convincing evidence for neutrino oscillations implying that neutrinos have mass.



$$\pi \longrightarrow \mu\, \nu_\mu$$
$$\hookrightarrow e\, \nu_\mu \nu_e$$



EXPECT $$\frac{N_{\nu_\mu}}{N_{\nu_e}} \approx 2$$

Super-Kamiokande results indicate a deficit of ν_μ from the upwards direction.

- ★ **Interpreted as $\nu_\mu \rightarrow \nu_\tau$ OSCILLATIONS**
- ★ **Implies neutrino MIXING and that neutrinos have mass.**

Detecting Neutrinos

Neutrinos are detected by observing the lepton produced in CHARGED CURRENT interactions with nuclei.

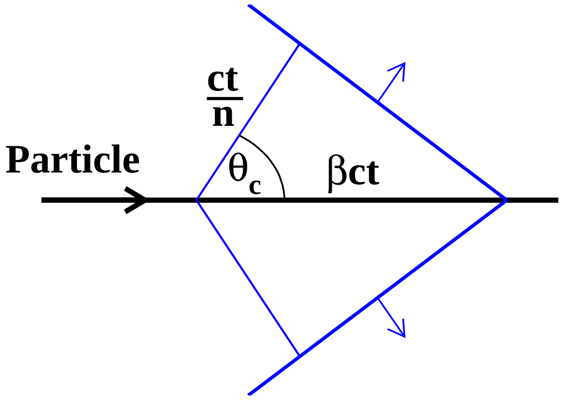
$$\begin{aligned} e.g.\quad \nu_e + N &\rightarrow e^- + X \\ \overline{\nu}_\mu + N &\rightarrow \mu^+ + X \end{aligned}$$

Size Matters:

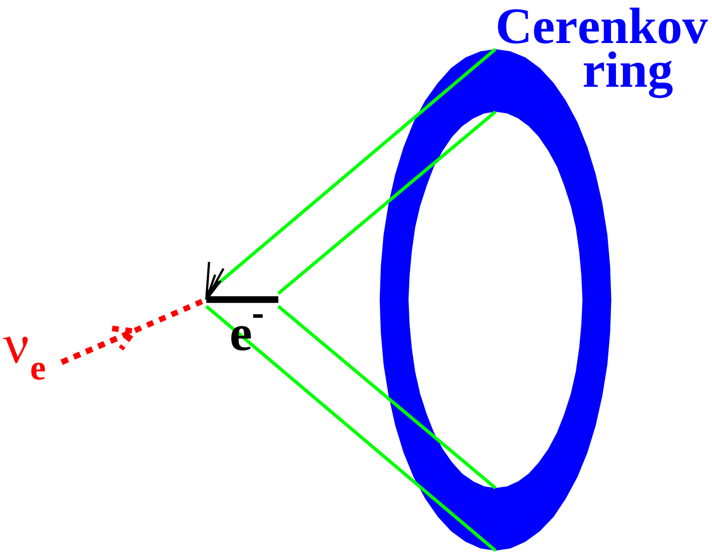
- ★ Neutrino mean free path in water $\sim$ light-years.
- ★ To detect atmospheric neutrinos - require very large mass detectors
- ★ Require them to be “cheap” therefore simple
- ★ Water Čerenkov detection

Čerenkov radiation

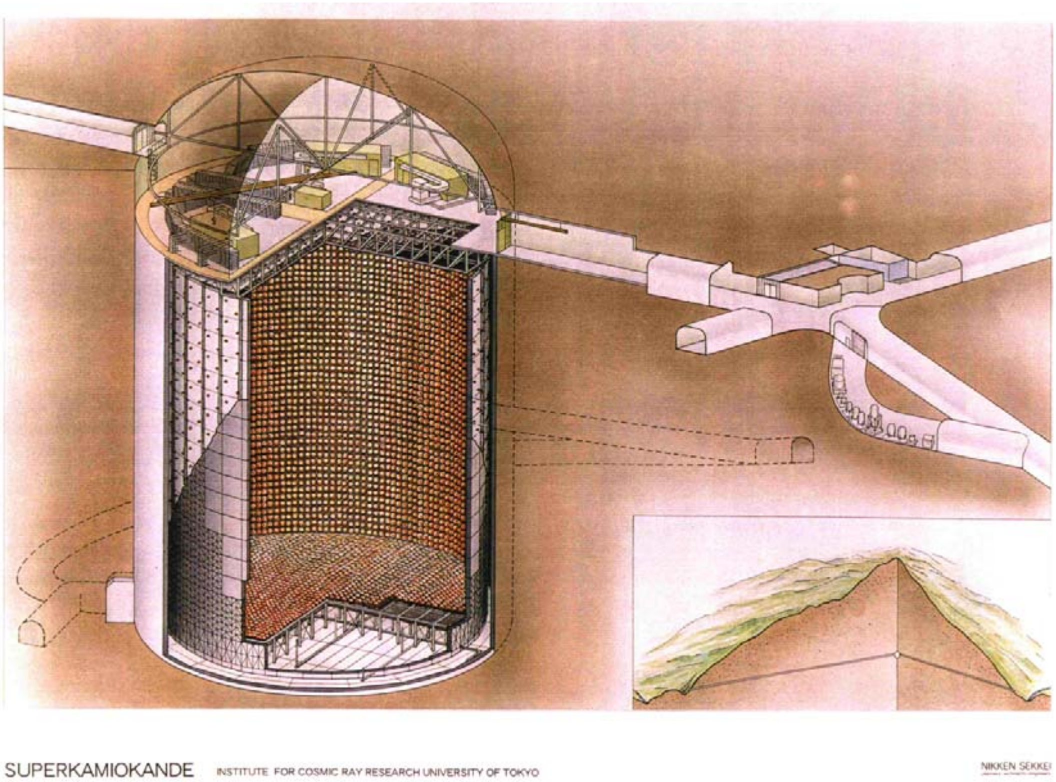
- ★ When a charged particle traverses a dielectric medium, light is emitted by excited atoms
- ★ A coherent wavefront forms (Čerenkov Radiation) whenever the velocity of a charged particle exceeds c/n (n=refractive index).
- ★ Čerenkov Radiation is emitted in a cone i.e. at a fixed angle with respect to the particle.

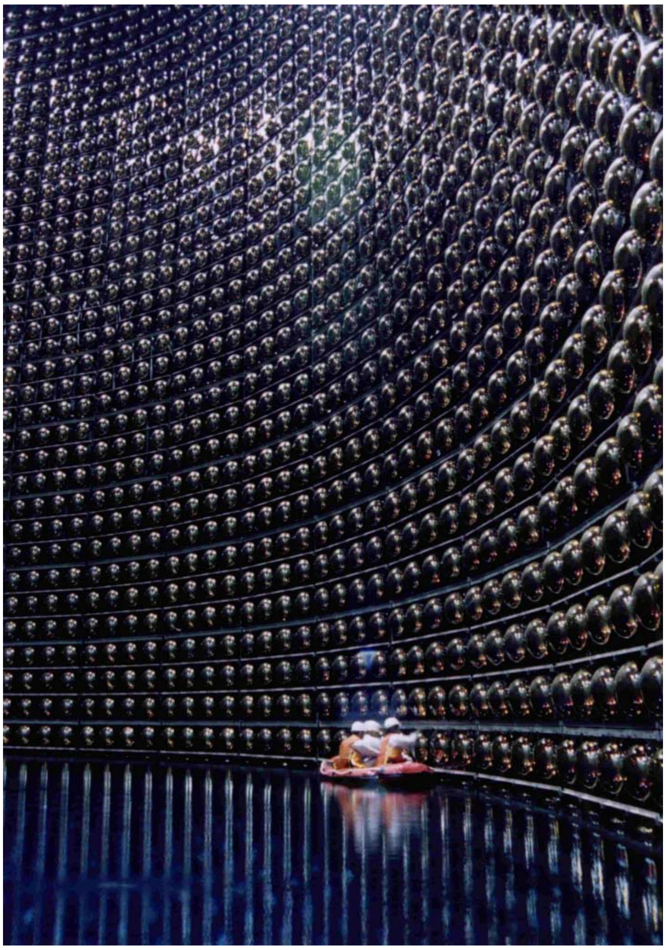


$$\cos\theta_c = \frac{c}{nv} = \frac{1}{n\beta}$$



SuperKamiokande



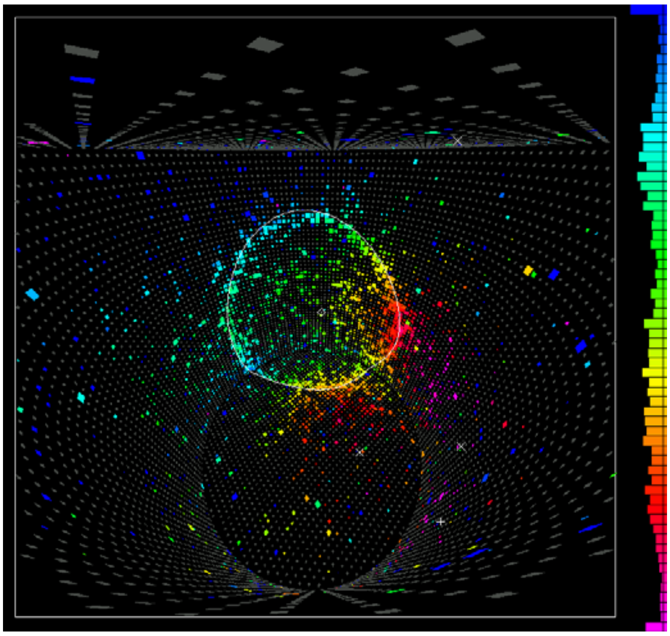


SuperKamiokande

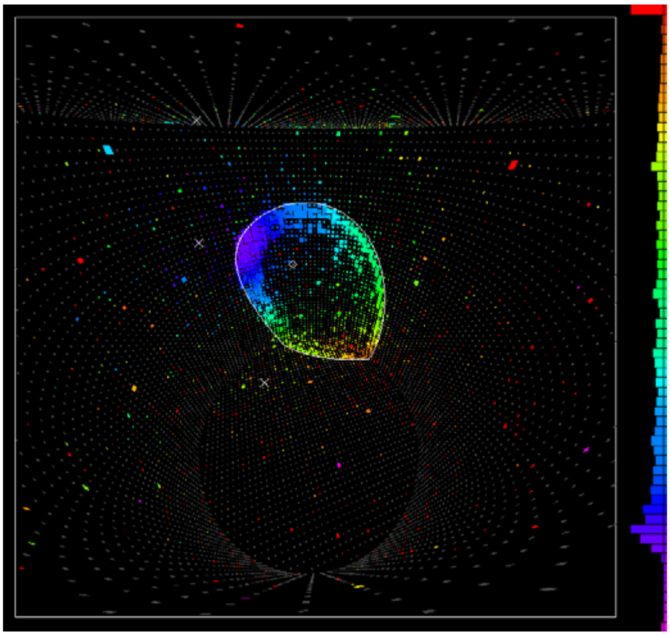
Water Čerenkov Detector

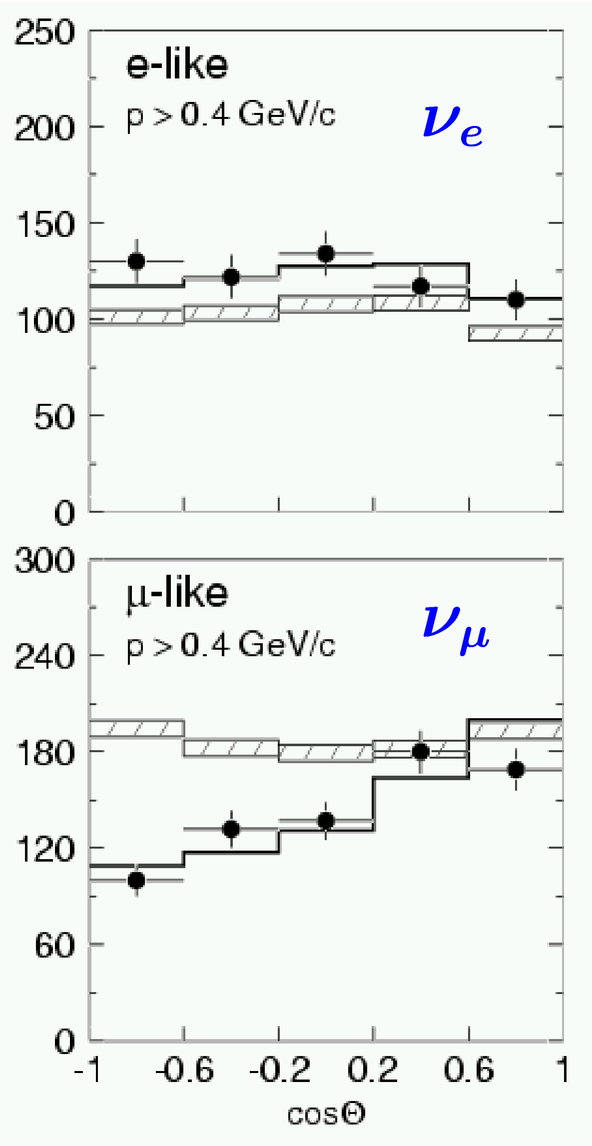
- ★ **50,000 tons of water**
- ★ **Surrounded by 11,146 50 cm diameter photo-multiplier tubes**

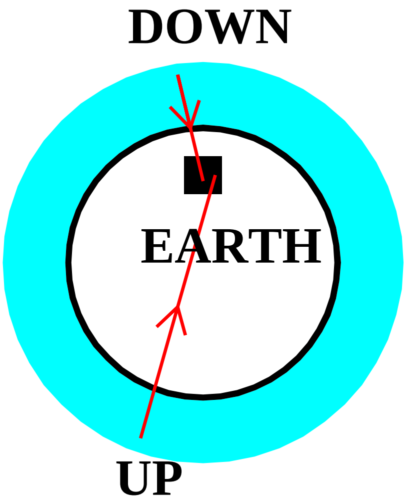
$\nu_e + N \rightarrow e^- + X$

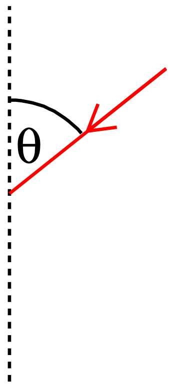


$\nu_\mu + N \rightarrow \mu^- + X$









Expect

- ★ Isotropic (flat) distributions in $\cos\theta$.
- ★ $N(\nu_\mu) \sim 2N(\nu_e)$

Observe

- ★ Deficit of ν_μ from BELOW

Interpretation

- ★ $\nu_\mu \rightarrow \nu_\tau$ OSCILLATIONS
- ★ Neutrinos have MASS

Neutrino Mixing

Neutrinos with Mass

The quark states which take part in the WEAK interaction (d', s') are related to the states with unique mass (d,s).

$$\begin{pmatrix} d' \\ s' \end{pmatrix} = \begin{pmatrix} \cos\theta_c & \sin\theta_c \\ -\sin\theta_c & \cos\theta_c \end{pmatrix} \begin{pmatrix} d \\ s \end{pmatrix}$$

Assume the same thing happens for neutrinos:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

Consider only the first two generations. The WEAK interaction states (**WEAK EIGENSTATES**) are ν_e, ν_μ. These are related to the **MASS EIGENSTATES** ν_1, ν_2.

- ★ e.g. in π^+-decay produce the μ^+ and ν_μ *i.e.* the state that couples to the weak interaction
- ★ e.g. ν_μ corresponds to a linear combination of the states with definite mass, $\overline{\nu}_1$ and $\overline{\nu}_2$.

$$\begin{aligned} \nu_e &= +\cos\theta\nu_1 + \sin\theta\nu_2 \\ \nu_\mu &= -\sin\theta\nu_1 + \cos\theta\nu_2 \end{aligned}$$

or expressing the mass eigenstates in terms of the weak eigenstates

$$\begin{aligned} \nu_1 &= +\cos\theta\nu_e - \sin\theta\nu_\mu \\ \nu_2 &= +\sin\theta\nu_e + \cos\theta\nu_\mu \end{aligned}$$

Suppose a muon neutrino with momentum $\tilde{\mathrm{p}}$ is produced in a WEAK decay, *e.g.* $\pi^+ \rightarrow \mu^+\nu_\mu$,

At $t = 0$ the wave-function $\psi(\tilde{\mathrm{p}}, t{=}0)$:

$$\begin{aligned} \psi(\tilde{\mathrm{p}}, t{=}0) &= \nu_\mu(\tilde{\mathrm{p}}) \\ &= \cos\theta\nu_2(\tilde{\mathrm{p}}) - \sin\theta\nu_1(\tilde{\mathrm{p}}) \end{aligned}$$

The time dependent parts wave-function are given by

$$\nu_1(\tilde{p},t) = a_1(t)\nu_1(\tilde{p}) \quad \text{with} \quad a_1(t) = e^{-iE_1t}$$
$$\nu_2(\tilde{p},t) = a_2(t)\nu_2(\tilde{p}) \quad \text{with} \quad a_2(t) = e^{-iE_2t}$$

After time t

$$\begin{aligned}
\psi(\tilde{p},t) &= a_2(t)\cos\theta\nu_2(\tilde{p}) - a_1(t)\sin\theta\nu_1(\tilde{p}) \\
&= a_2(t)\cos\theta\left[\cos\theta\nu_\mu(\tilde{p}) + \sin\theta\nu_e(\tilde{p})\right] \\
&\quad -a_1(t)\sin\theta\left[\cos\theta\nu_e(\tilde{p}) - \sin\theta\nu_\mu(\tilde{p})\right] \\
&= \left[a_1(t)\sin^2\theta + a_2(t)\cos^2\theta\right]\nu_\mu(\tilde{p}) \\
&\quad +\sin\theta\cos\theta[a_2(t) - a_1(t)]\nu_e(\tilde{p}) \\
&= c_\mu\nu_\mu(\tilde{p}) + c_e\nu_e(\tilde{p})
\end{aligned}$$

Probability of oscillating into ν_e is given by $|c_e|^2$

IF neutrinos are massless $E_1 = E_2 = |\tilde{p}|$ at all times the state remains $\nu_\mu(\tilde{p})$. However if ν_1 and ν_2 have different masses a phase difference arises and the neutrino (which was initially ν_μ) can be observed as the ν_e

Probability of oscillating into ν_e:

$$\begin{aligned}
P(\nu_e) &= |c_e|^2 = |\sin\theta\cos\theta[a_2(t) - a_1(t)]|^2 \\
&= \frac{1}{4}\sin^2 2\theta(e^{-iE_2t} - e^{-iE_1t})(e^{iE_2t} - e^{iE_1t}) \\
&= \frac{1}{4}\sin^2 2\theta(2 - e^{i(E_2-E_1)t} - e^{-i(E_2-E_1)t}) \\
&= \sin^2 2\theta\sin^2\left[\frac{(E_2 - E_1)}{2}t\right]
\end{aligned}$$

but $$E^2 = p^2 + m^2 = p\left(1 + \frac{m^2}{p^2}\right)^{\frac{1}{2}}$$

therefore $$E \approx p + \frac{m^2}{2p} \quad \text{for } m \ll E$$

$$E_2(p) - E_1(p) \approx \frac{m_2^2 - m_1^2}{2p} \approx \frac{m_2^2 - m_1^2}{2E}$$

$$P(\nu_\mu \to \nu_e) = \sin^2 2\theta \sin^2\left(\frac{\Delta m^2 t}{4E}\right)$$

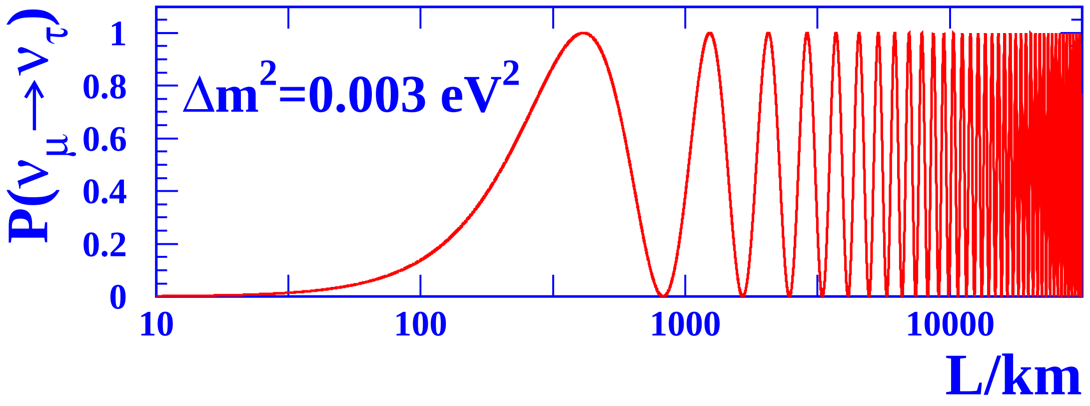
Equivalent expression for $\nu_\mu \to \nu_\tau$:

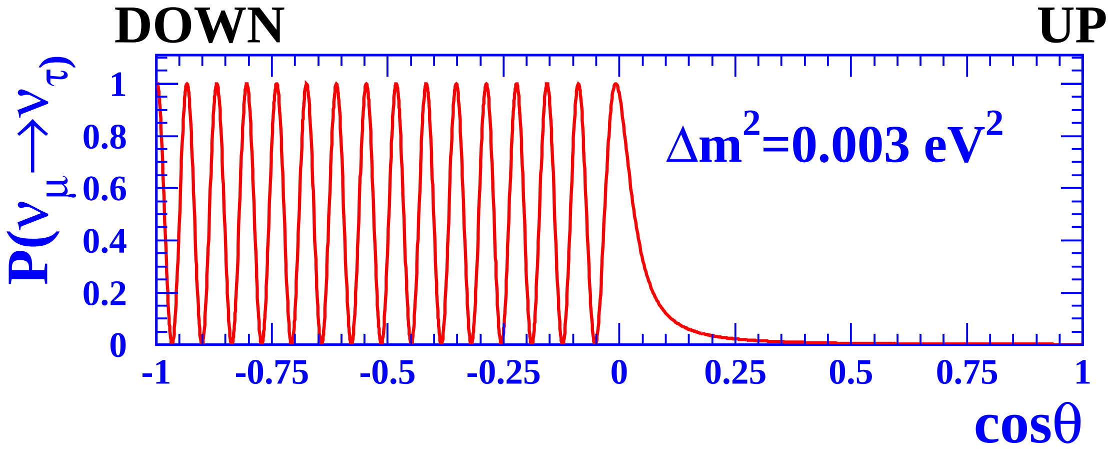
$$\boxed{P(\nu_\mu \to \nu_\tau) = \sin^2 2\theta \sin^2\left(\frac{1.27(m_3^2 - m_2^2)L}{E}\right)}$$

here **L** is the distance traveled in km, Δm^2 is the mass difference in $(eV)^2$ and E_ν is the neutrino energy in GeV.

Interpretation of Super-Kamiokande Results

For $E_{\nu_\mu} = 1\ \mathrm{GeV}$ (typical of atmospheric neutrinos)





Results consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillations:

- ★ $|m_3^2 - m_2^2| \sim 2.5 \times 10^{-3}$eV^2
- ★ Maximal mixing *i.e.* $\sin^2\theta \approx 1$

Solar Neutrino Oscillations

Also compelling evidence for oscillations of ν_e neutrinos produced in the sun (see Nuclear Course) $\nu_e \rightarrow \nu_\mu$ and $\nu_e \rightarrow \nu_\tau$?

Neutrino Oscillations : Comments

- ★ Super-Kamiokande results are convincing !
- ★ Neutrinos almost certainly have mass
- ★ Neutrino oscillation only sensitive to mass differences.
- ★ Recent results (2002/2003)

  SNO on solar neutrinos and

  KamLand on reactor neutrinos:

  suggest $|m_2^2 - m_1^2| \approx 10^{-5}$ eV^2
- ★ If mass states $\nu_3 > \nu_2 > \nu_1$, then it is tempting to identify

$$m_{\nu_3} \sim \sqrt{2.5 \times 10^{-3}}\ \text{eV} \sim 0.05\ \text{eV}.$$

$$m_{\nu_2} \sim \sqrt{10^{-5}}\ \text{eV} \sim 0.003\ \text{eV}.$$

- ★ This is a very active area of research. New accelerator based experiments coming online soon (*e.g.* MINOS starts early 2005).
- ★ Our understanding of neutrinos is evolving rapidly.
- ★ Do not understand why neutrino masses are so small !

(see Question 17 on the problem sheet)

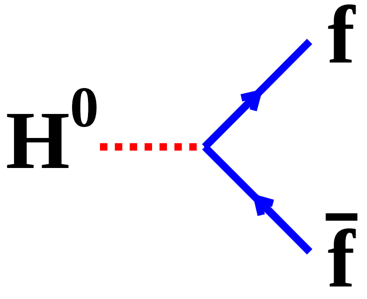
The Higgs Boson

There is one final ingredient to the Standard Model - the Higgs Boson.

The Standard Model requires the existence of a new neutral SCALAR (i.e. spin-0) particle - the HIGGS boson.

Higgs Boson and Mass

- The Higgs Boson (if it exists) is the particle responsible for the MASS of ALL particles (including the $W^{\pm}$ and Z^{0}).
- The Higgs Field has a non-zero vacuum expectation value, it is a property of the vacuum.
- As particles move through the vacuum they interact with the non-zero Higgs field
- It is this interaction that gives fermions mass
- The strength of the Higgs coupling to fermions is proportional to mass

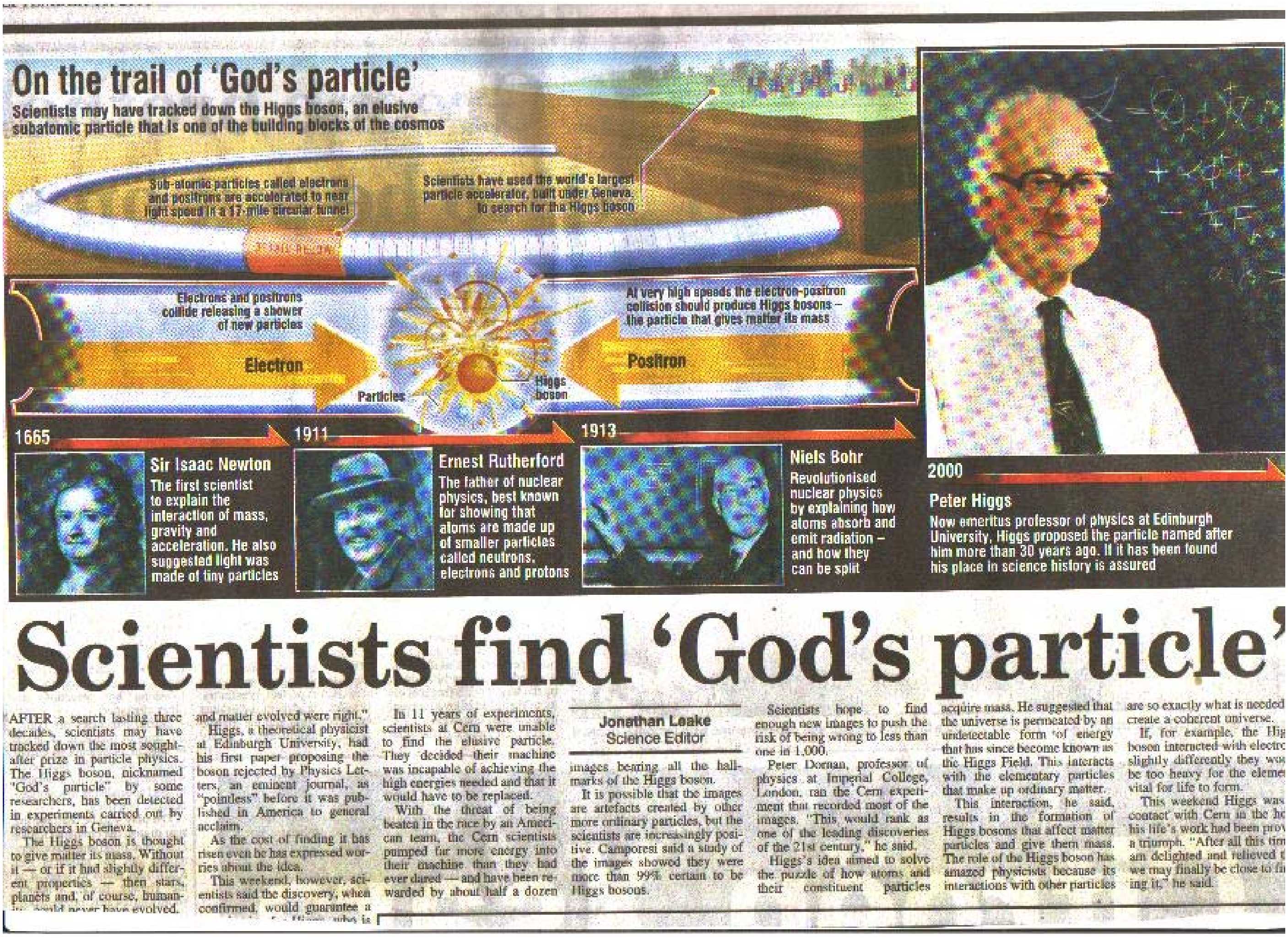


$$g_{Hff} = (\sqrt{2}G_{\mathrm{F}})^{\frac{1}{2}} m_f$$

M. Veltman, Scientific American 255 (1986) 88.

Discovery of the Higgs Boson ?

'Sunday Times', 10/9/2000



On the trail of 'God's particle'

Scientists may have tracked down the Higgs boson, an elusive subatomic particle that is one of the building blocks of the cosmos

Sub-atomic particles called electrons and positrons are accelerated to near light speed in a 17-mile circular tunnel

Scientists have used the world's largest particle accelerator, built under Geneva, to search for the Higgs boson

Electrons and positrons collide releasing a shower of new particles

At very high speeds the electron-positron collision should produce Higgs bosons – the particle that gives matter its mass

1665

Sir Isaac Newton
The first scientist to explain the interaction of mass, gravity and acceleration. He also suggested light was made of tiny particles

1911

Ernest Rutherford
The father of nuclear physics, best known for showing that atoms are made up of smaller particles called neutrons, electrons and protons

1913

Niels Bohr
Revolutionised nuclear physics by explaining how atoms absorb and emit radiation – and how they can be split

2000

Peter Higgs
Now emeritus professor of physics at Edinburgh University, Higgs proposed the particle named after him more than 30 years ago. If it has been found his place in science history is assured

Scientists find 'God's particle'

AFTER a search lasting three decades, scientists may have tracked down the most sought-after prize in particle physics. The Higgs boson, nicknamed "God's particle" by some researchers, has been detected in experiments carried out by researchers in Geneva.

The Higgs boson is thought to give matter its mass. Without it — or if it had slightly different properties — then stars, planets and, of course, humanity would never have evolved.

and matter evolved were right."

Higgs, a theoretical physicist at Edinburgh University, had his first paper proposing the boson rejected by Physics Letters, an eminent journal, as "pointless" before it was published in America to general acclaim.

As the cost of finding it has risen even he has expressed worries about the idea.

This weekend, however, scientists said the discovery, when confirmed, would guarantee a [illegible] Higgs, who is

In 11 years of experiments, scientists at Cern were unable to find the elusive particle. They decided their machine was incapable of achieving the high energies needed and that it would have to be replaced.

With the threat of being beaten in the race by an American team, the Cern scientists pumped far more energy into their machine than they had ever dared — and have been rewarded by about half a dozen

Jonathan Leake
Science Editor

images bearing all the hallmarks of the Higgs boson.

It is possible that the images are artefacts created by other more ordinary particles, but the scientists are increasingly positive. Camporesi said a study of the images showed they were more than 99% certain to be Higgs bosons.

Scientists hope to find enough new images to push the risk of being wrong to less than one in 1,000.

Peter Dornan, professor of physics at Imperial College, London, ran the Cern experiment that recorded most of the images. "This would rank as one of the leading discoveries of the 21st century," he said.

Higgs's idea aimed to solve the puzzle of how atoms and their constituent particles acquire mass. He suggested that the universe is permeated by an undetectable form of energy that has since become known as the Higgs Field. This interacts with the elementary particles that make up ordinary matter.

This interaction, he said, results in the formation of Higgs bosons that affect matter particles and give them mass. The role of the Higgs boson has amazed physicists because its interactions with other particles are so exactly what is needed create a coherent universe.

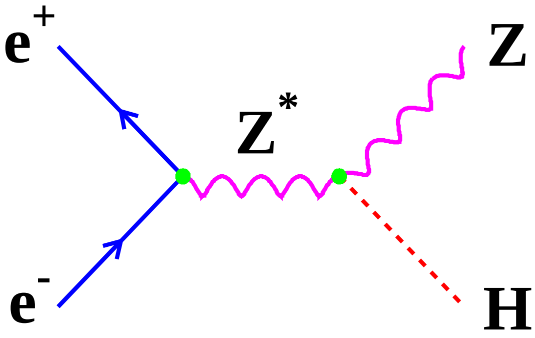
If, for example, the Hig boson interacted with electro slightly differently they wo be too heavy for the eleme vital for life to form.

This weekend Higgs was contact with Cern in the ho his life's work had been prov a triumph. "After all this tim am delighted and relieved t we may finally be close to fi ing it," he said.

Has the Higgs boson been seen at LEP ?

Higgs Production at LEP

IF $m_H < \sqrt{s} - M_{Z^0}$

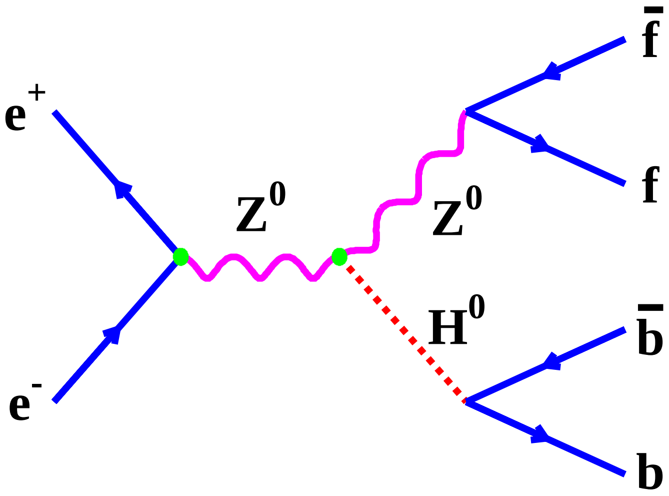


In 2000 LEP operated with $\sqrt{s} \approx 207$ GeV, therefore had the potential to discover the Higgs Boson IF $m_H < 116$ GeV

Higgs Decay

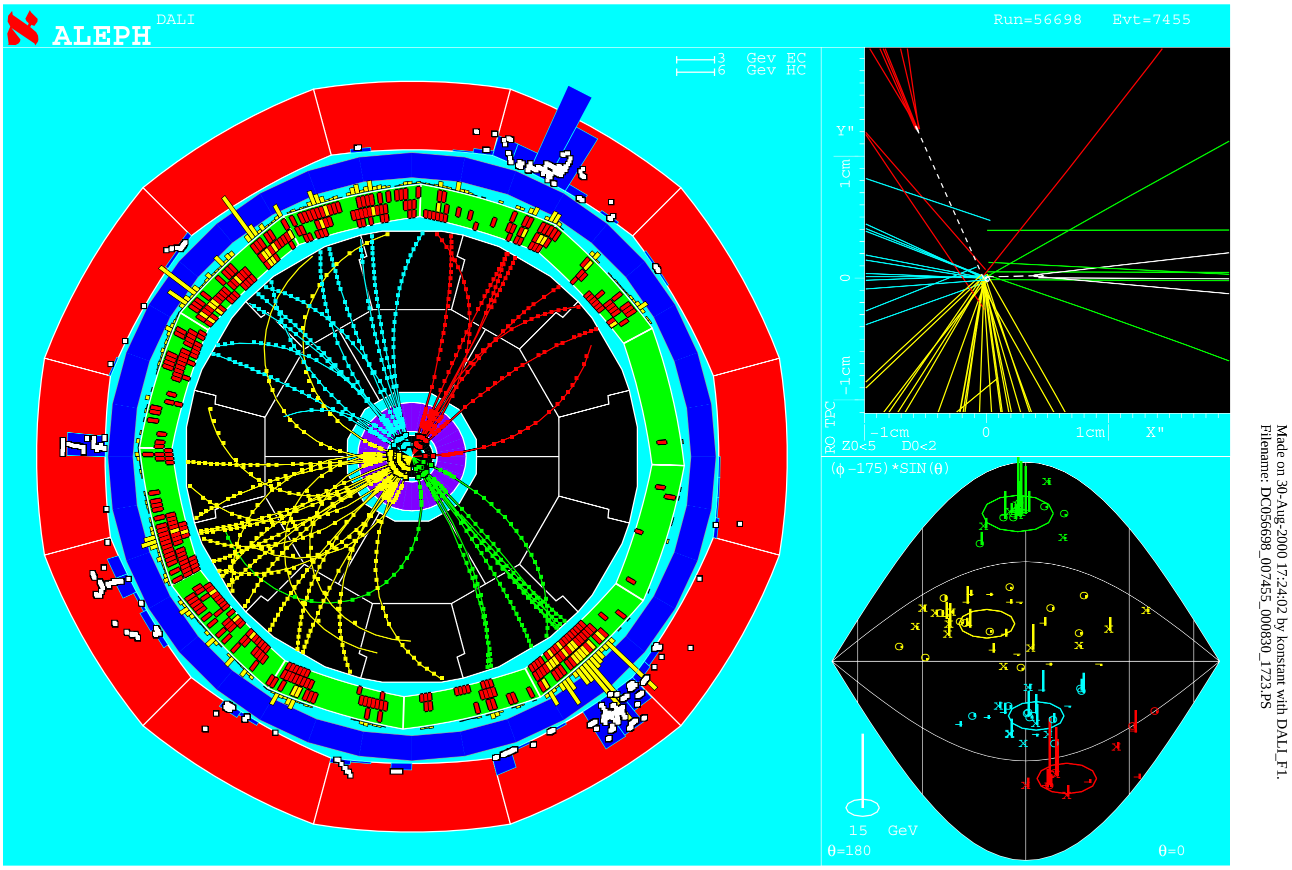
- ★ The Higgs boson ‘couples’ to mass.
- ★ Consequently partial widths proportional to m^2 of the particle involved
- ★ The Higgs Boson decays preferentially to the most massive particle kinematically allowed (*i.e.* energy conservation)
- ★ For $m_H < 116$ GeV this is the b-quark

At LEP search for $\mathrm{e^+e^-} \rightarrow \mathrm{H^0Z^0} \rightarrow \mathrm{b\bar{b}f\bar{f}}$

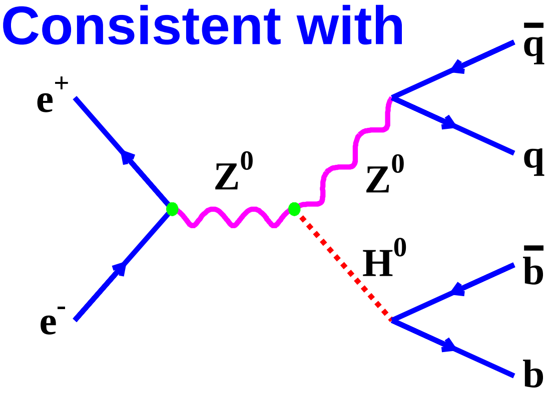


The Evidence....

4 Possible $e^+e^- \to Z^0H^0$ events observed in the final year of LEP operation. *e.g.*



Consistent with



$$\boxed{m_{H^0} = 115\ \mathrm{GeV}}$$

- ★ The evidence is tantalizing **BUT FAR FROM** conclusive
- ★ LEP operation ended in October 2000
- ★ WAIT another 3^+ years for LEP’s successor at CERN - the Large Hadron Collider (LHC).

CONCLUSION

The Standard Model WORKS !

- ★ The Standard Model **describes** ALL experimental observations
- ★ ALL particles of SM have been discovered with the exception of the Higgs.
- ★ Highly predictive theory - tested to high precision at an energy scale of $\sqrt{s} = 100$ GeV

BUT many many questions

- ★ Too many free parameters (over 20): G_{F}, M_{Z^0}, α_{em}, α_S, 12 fermion masses, quark and ν mixing matrices, the Higgs boson.
- ★ The Standard Model is just that - a model rather than anything more fundamental.
- ★ Do not understand the origin of fermion masses.
- ★ Why 3 generations ?
- ★ Are leptons/quarks fundamental - substructure ?
- ★ The Higgs model has problems $\longrightarrow$ huge cosmological constant.
- ★ Need to unify all forces : GRAND UNIFICATION
- ★ Ultimately gravity needs to be included
- ★ + many other fundamental questions......

Over the course of the last 30 years out understanding of Particle Physics has changed beyond recognition.

Through precise measurements and powerful theoretical ideas our understanding is still evolving.

In the next few years hope for yet more surprises!