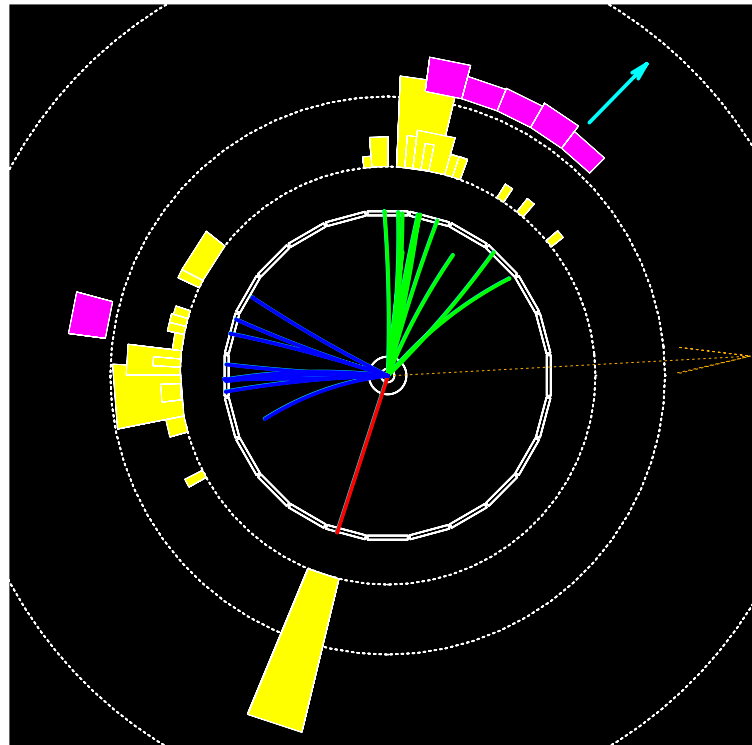


An Introduction to Modern Particle Physics

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Science Summer School: 30th July - 1st August 2007

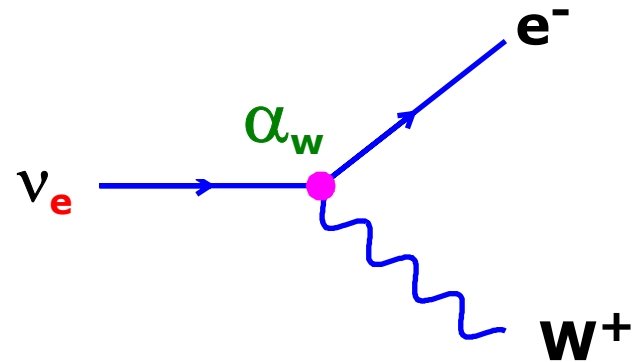
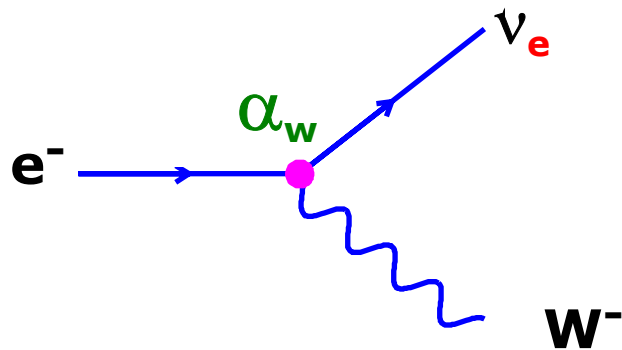
Course Synopsis

- ★ **Introduction : Particles and Forces**
 - what are the fundamental particles
 - what is a force
- ★ **The Electromagnetic Interaction**
 - QED and e^+e^- annihilation
 - the Large Electron-Positron collider
- ★ **The Crazy world of the Strong Interaction**
 - QCD, colour and gluons
 - the quarks
- ★ **The Weak interaction**
 - W bosons
 - Neutrinos and Neutrino Oscillations
 - The MINOS Experiment
- ★ **The Standard Model (what we know) and beyond**
 - Electroweak Unification
 - the Z boson
 - the Higgs Boson
 - Dark matter and supersymmetry
 - Unanswered questions

Why So WEAK ?

RECALL:

- **Electromagnetic Force** : massless photon : $\alpha \approx 1/100$
- **Strong Force** : massless gluon : $\alpha_s \approx 1$
- **Weak Force** : **massive W** : $\alpha_w \approx ?$



$$\alpha_w \sim 1/40 !$$

- ★ The **weak** interaction has **almost the same** intrinsic strength as the **EM** force !
- ★ Suggestive of **UNIFICATION OF FORCES**
- ★ Only weak because need a lot of energy to “make” a W-boson (recall easier to emit low energy virtual particles)

Recap

Electromagnetic Interaction:

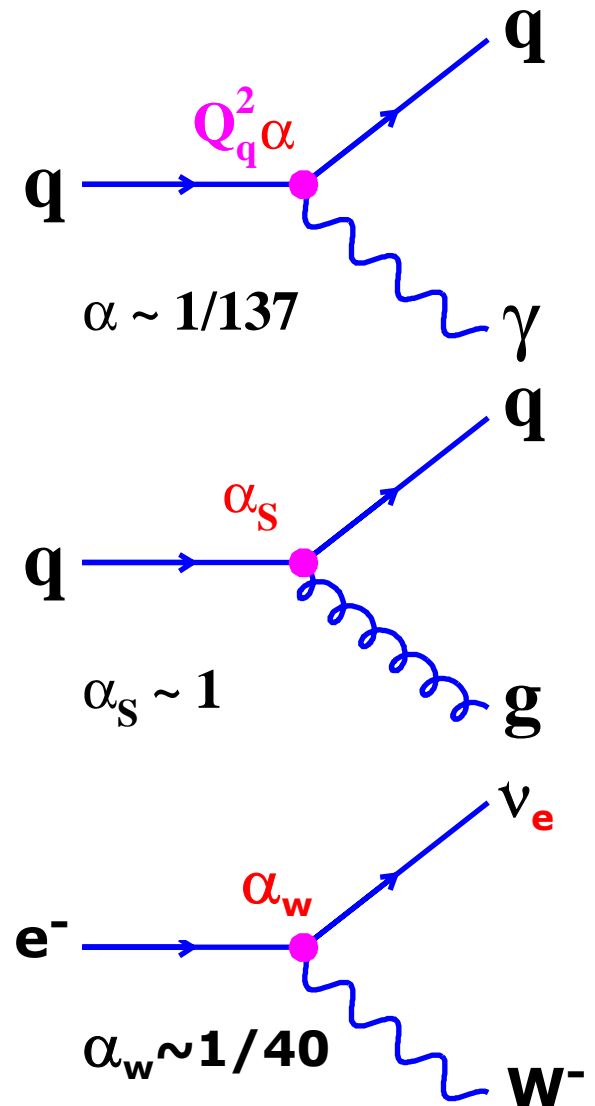
- ★ Mediated by **massless photons**
- ★ Photon couples to **ELECTRIC** charge
- ★ **Does not change flavour**
- ★ **QUARKS/CHARGED LEPTONS**

Strong Interaction:

- ★ Mediated by **massless GLUONS**
- ★ **GLUON** couples to **"COLOUR"** charge
- ★ **Does not change flavour**
- ★ **QUARKS/GLUONS**

Weak Interaction: **IS VERY DIFFERENT**

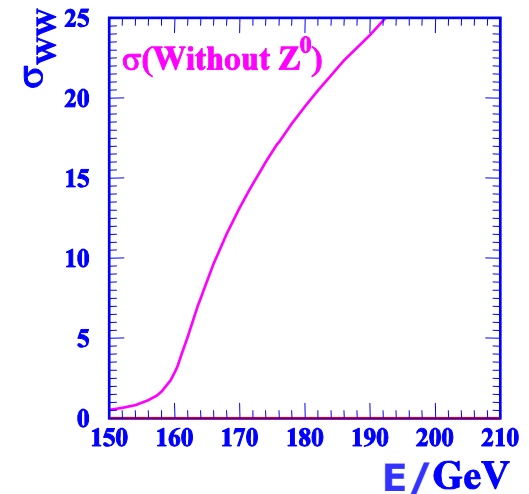
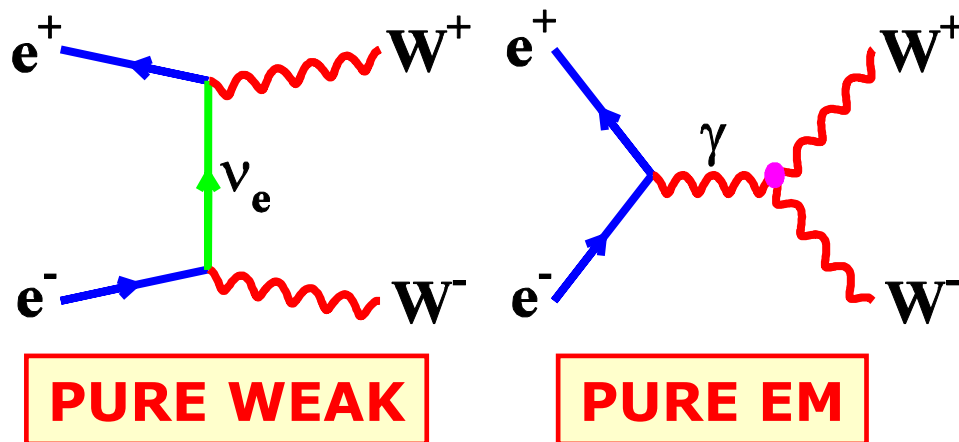
- ★ Mediated by **massive W BOSONS**
- ★ Couples to all particles equally
- ★ **Changes flavour**
- ★ **QUARKS/ALL LEPTONS**
- ★ **Only appears weak due to mass of W**
 $M_w \sim 80 \text{ GeV}/c^2$



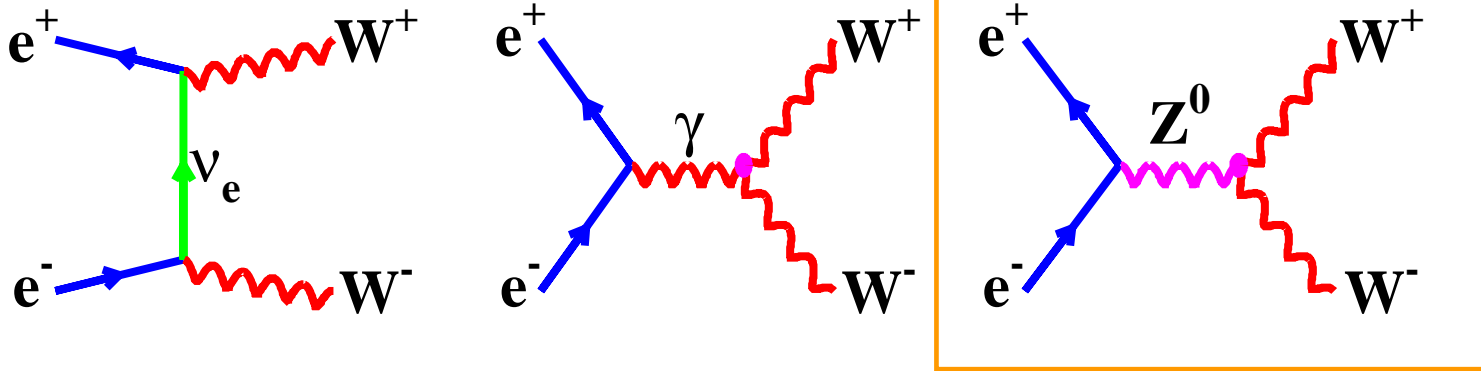
Electroweak Unification

Hints for Unification of WEAK and EM forces:

- ★ Strengths of **WEAK** and **EM** interactions are similar
- ★ Force carrying particle of the **WEAK** force is charged i.e. carries charge of the EM interaction
- ★ also consider $e^+e^- \rightarrow W^+W^-$ – 2 ways this can occur



- ★ Cross-section goes to infinity at high energies
- ★ Problem fixed by assuming another process



This prevents the cross-section increasing without limit !

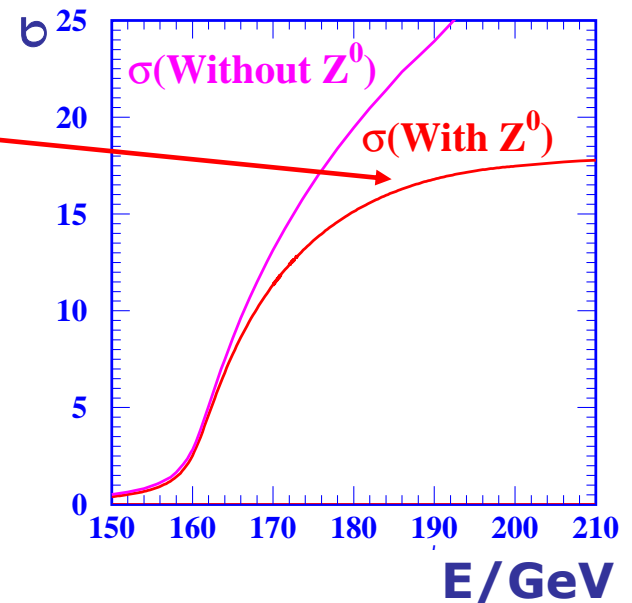
★ BUT only works if the couplings of the g , W^\pm and Z^0 are all related !

★ Z^0 is a QM mixture of a photon and neutral version of the W

★ Z^0 "acts like a neutral W-boson"

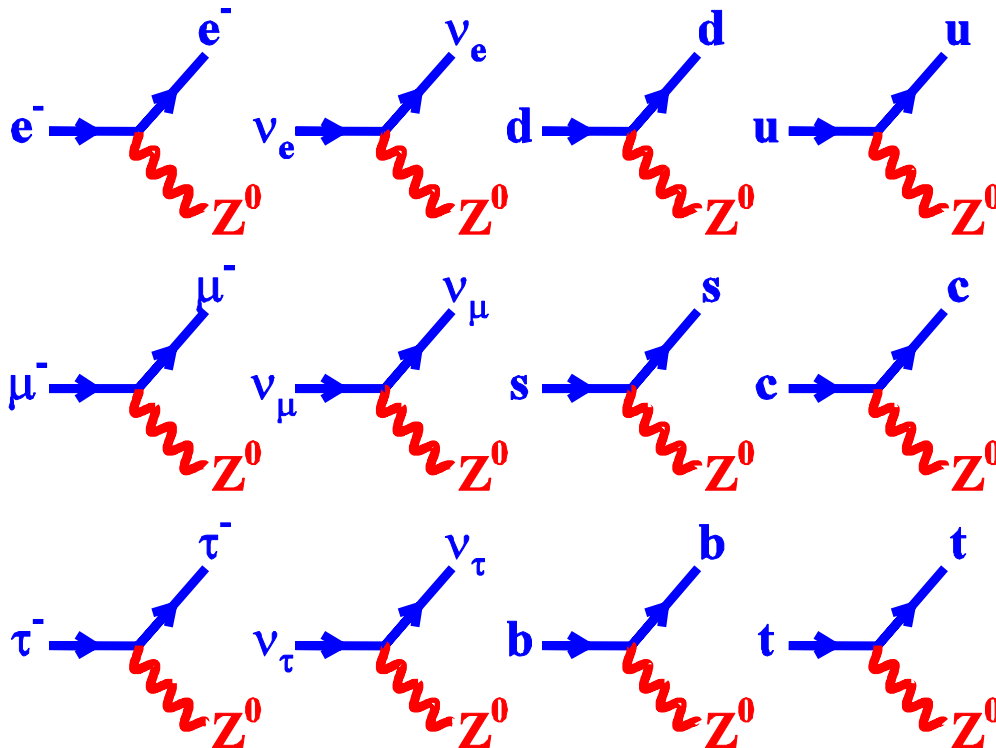
★ Z^0 "acts like a heavy photon"

★ Mass of Z^0 related to that of W



Neutral Weak Force

- ★ New force carrying boson – “new” force
- ★ Really a different aspect of the weak force
- called **NEUTRAL WEAK INTERACTION**
- ★ Mass of **Z** boson $\sim 90 \text{ GeV}/c^2 \rightarrow$ weak force



**Z couples to all
quarks and leptons
(including neutrinos)**

+ annihilation

The Standard Model

- ★ There are **12** fundamental particles + **12** anti-particles

Electron (e^-)	Muon (μ^-)	Tau (τ^-)
Neutrino 1 (ν_1)	Neutrino 2 (ν_2)	Neutrino 3 (ν_3)
Up Quark (u)	Charm Quark (c)	Top Quark (t)
Down Quark (d)	Strange Quark (s)	Bottom Quark (b)

- ★ and 4 fundamental forces

Strong

Weak

Electromagnetic

Gravity

- ★ Forces due to the exchange of particles:

QED : PHOTON, γ

QCD : 8 GLUONS, g

WEAK : W^+, W^-, Z

+ Electroweak Unification

+ Higgs Boson

- ★ Provides a perfect description of all current data

Z and W Physics at LEP

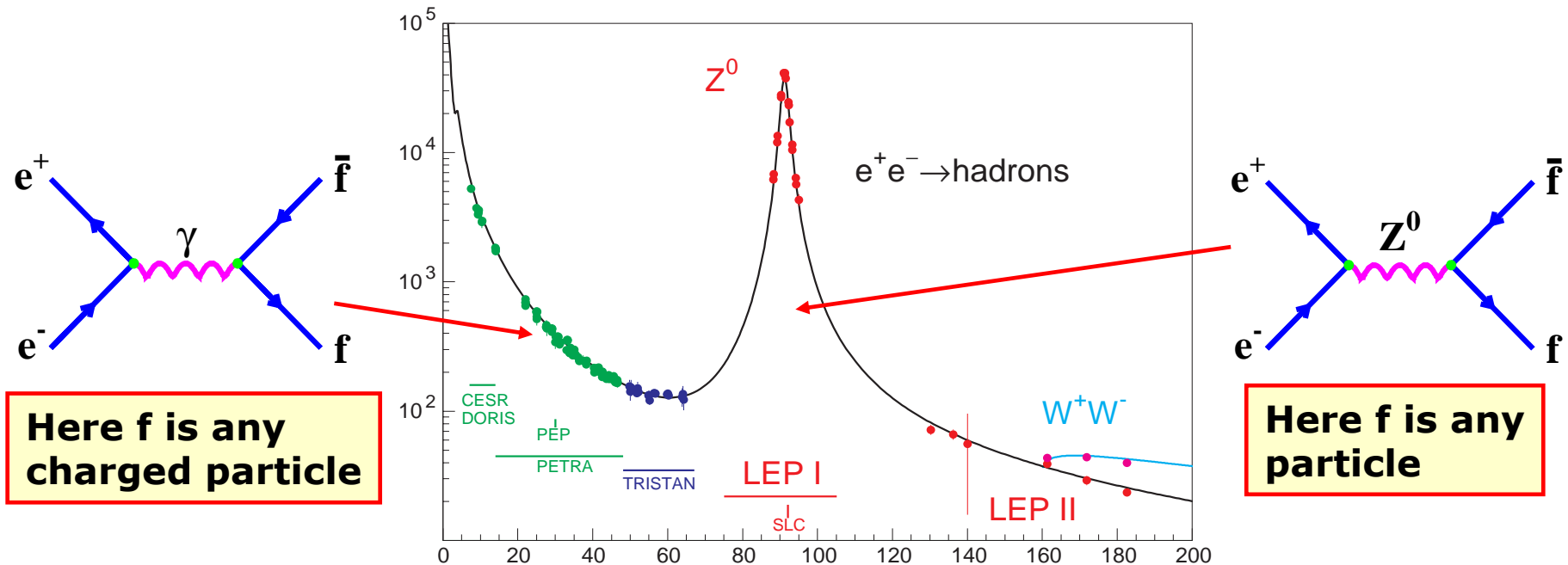


- ★ LEP designed as a **Z** and **W** factory
- ★ 1989-1995 $E = 91 \text{ GeV}$
 $e^+e^- \rightarrow \mathbf{Z} \rightarrow$
- ★ **16 million Zs** detected
- ★ 1996-2000 $E > 2M_{\mathbf{W}}c^2$
 $e^+e^- \rightarrow \mathbf{W}^+\mathbf{W}^- \rightarrow$
- ★ **30,000 $\mathbf{W}^+\mathbf{W}^-$** detected

- ★ Main emphasis on making very precise measurements of the properties of the **Z** and the **W**
- ★ In the Standard Model if you know e.g.
 $\alpha, \alpha_{\mathbf{W}}, M_{\mathbf{W}}$ can predict exactly $M_{\mathbf{Z}}$
- ★ Make precise measurements to test predictions of Standard Model

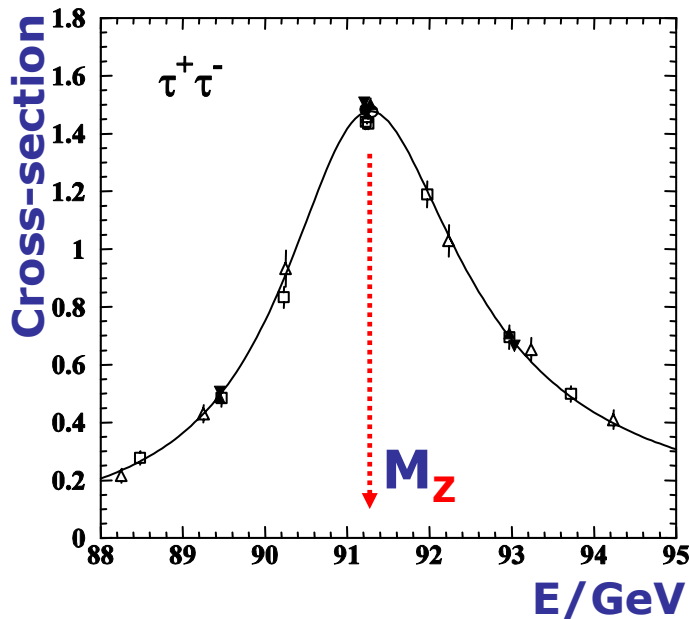
e^+e^- annihilation at the Z

- ★ Anything the **photon** can do so can the **Z** !
- ★ + **Z** can produce neutrinos



- ★ At energies lower than M_Z annihilation via the photon dominates
- ★ When the e^+e^- energy is almost exactly equal to M_Z get **resonant** production of Z and cross-section \uparrow

Measuring the Z Mass



Simple method:

★ Run accelerator at slightly different energies and the “peak energy” gives M_Z

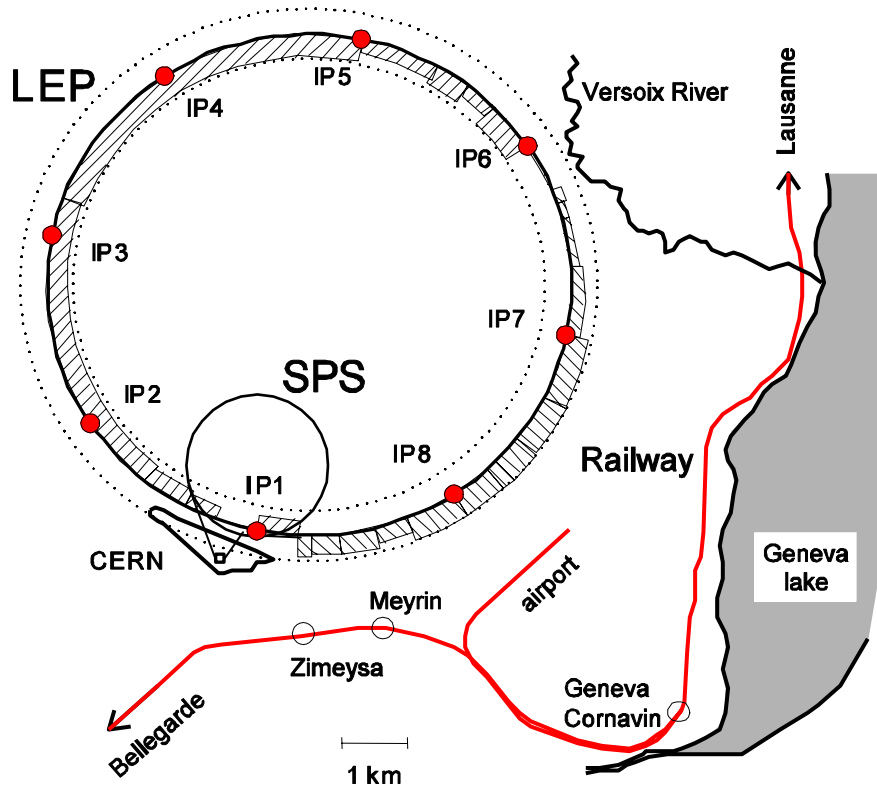
$$M_Z = 91.1875 \pm 0.0021 \text{ GeV}/c^2$$

★ Incredible precision - **0.002 %**
(for particle with lifetime 10^{-25} s)

Simple method – but in practice very hard !

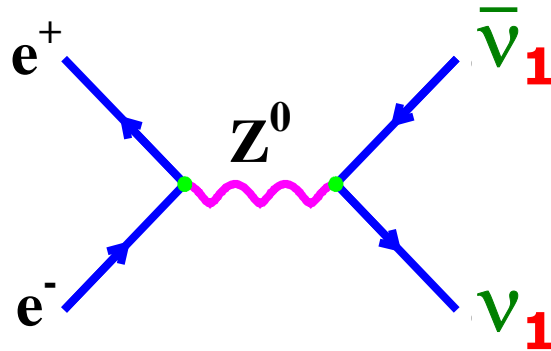
- As the moon orbits the Earth it distorts the rock in the Geneva area very very slightly !
- The nominal radius of the accelerator of 4.3 km varies by ± 0.15 mm enough to ruin the measurement
- therefore need to correct for tidal effects !

- **Also need a train timetable !**

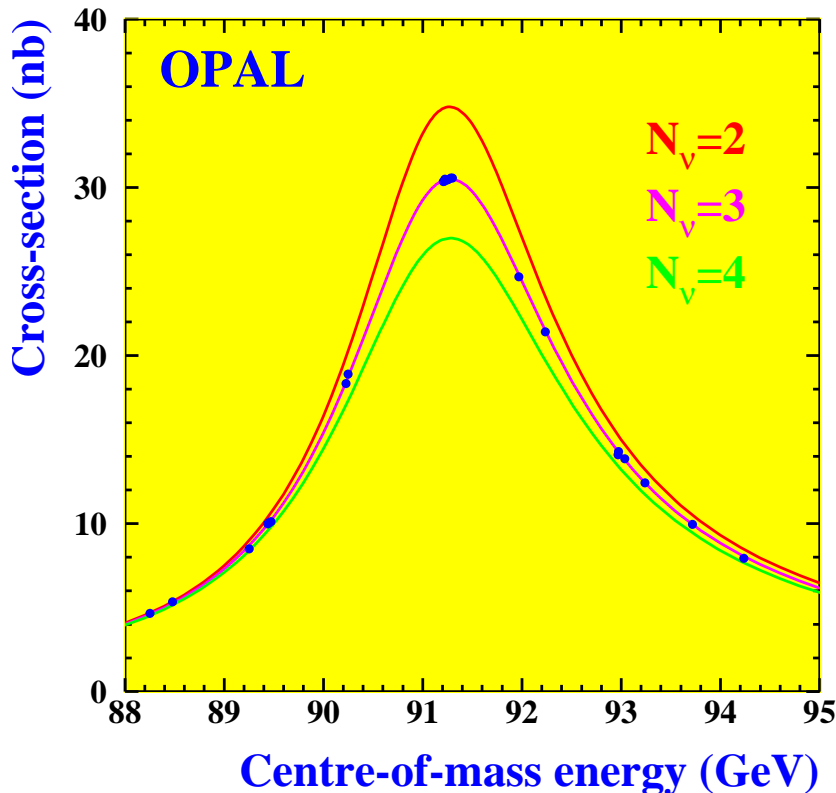


Leakage currents from the TGV rail via lake Geneva follow the path of least resistance using the LEP ring as a conductor. Everytime a train passes by the LEP beam energy changed very slightly

Number of Generations



- ★ Z can “decay” into all particle types provided $M_Z > 2m$
- ★ Even though you don't observe $e^+e^- \rightarrow \nu\bar{\nu}$ it does affect the shape of the peak

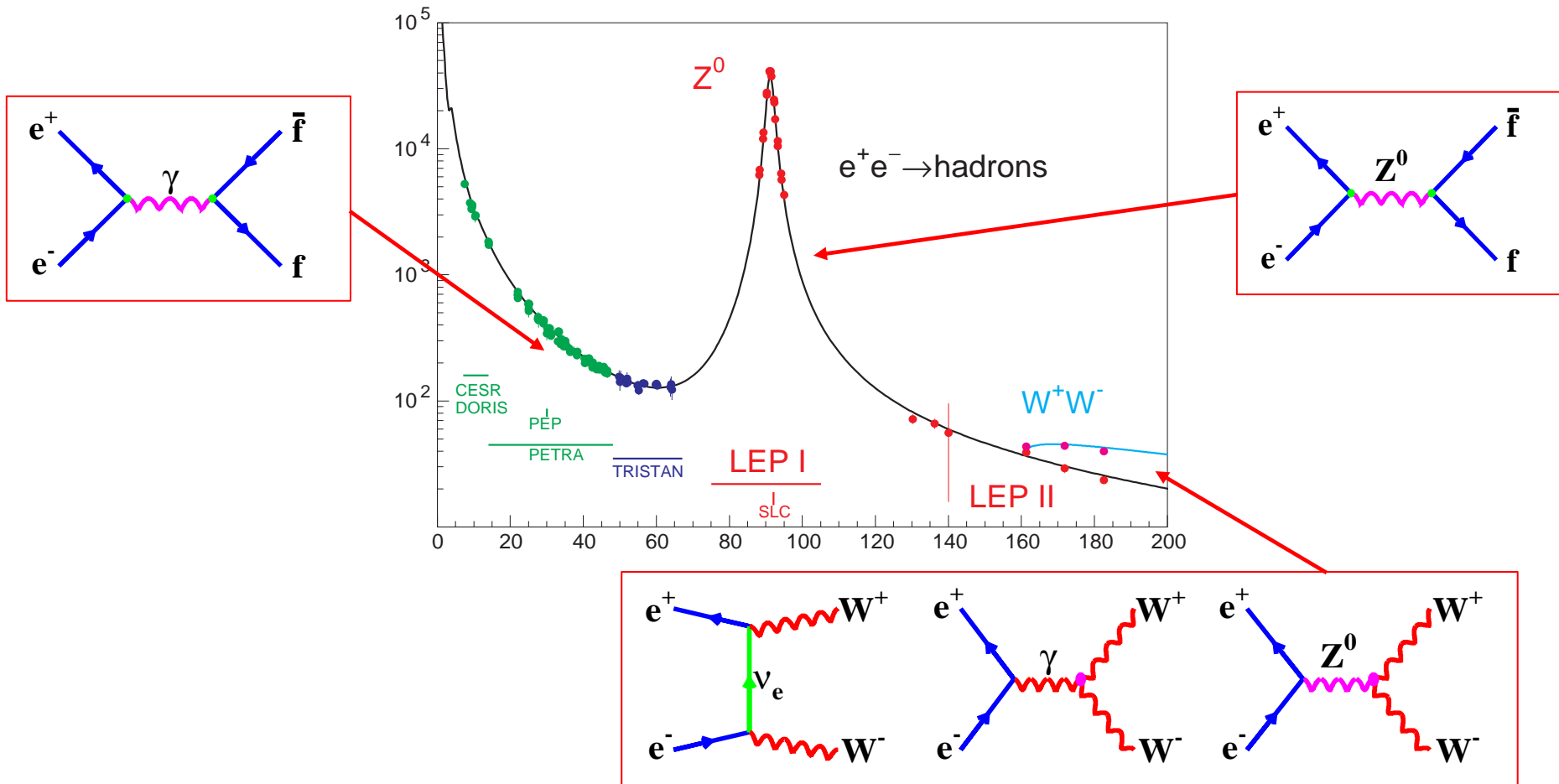


**3 GENERATIONS
OF NEUTRINO**

- ★ This is why we believe there are only 3 generations !
- ★ Don't understand why there are 3 generations !

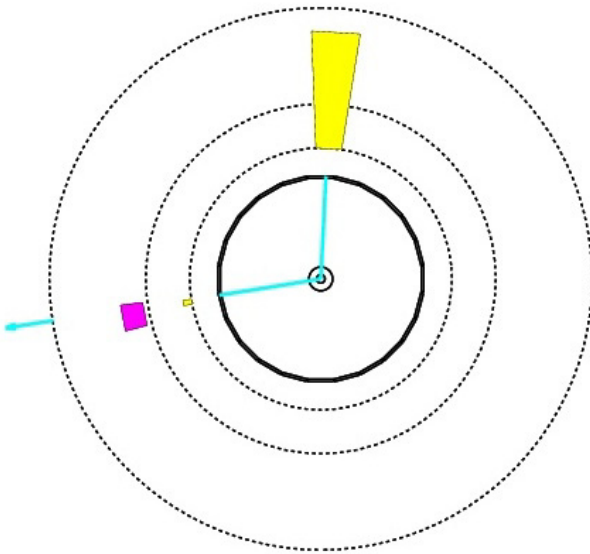
$$e^+e^- \rightarrow W^+W^-$$

★ Above the Z peak, produce pairs of W bosons when $E > 2M_W$, i.e. $E > 160$ GeV

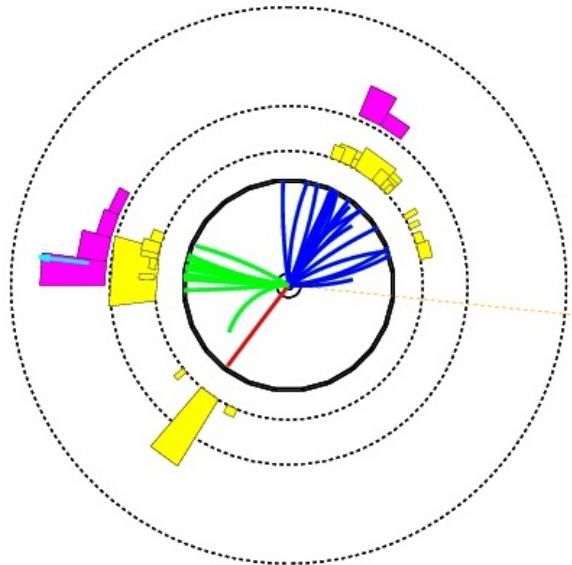


W Decay

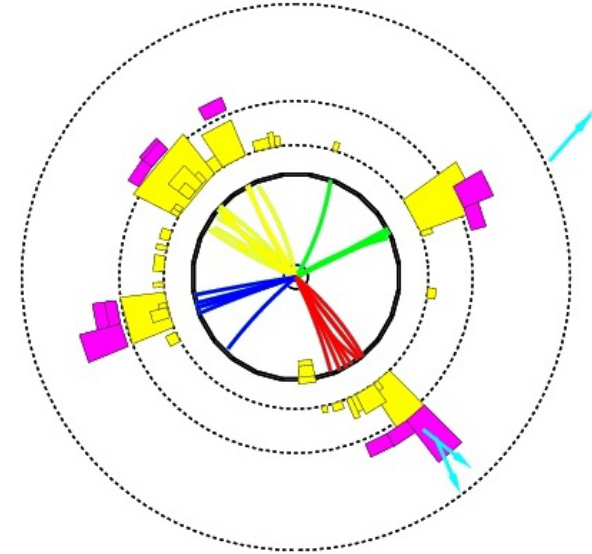
- ★ What do $e^+e^- \rightarrow W^+W^-$ events look like ?
- ★ 3 distinct topologies



Both Ws decay to a **charged lepton** and a **neutrino**



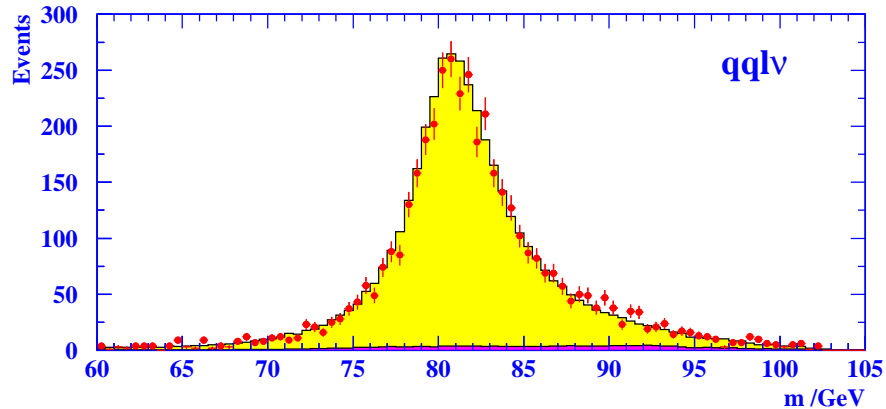
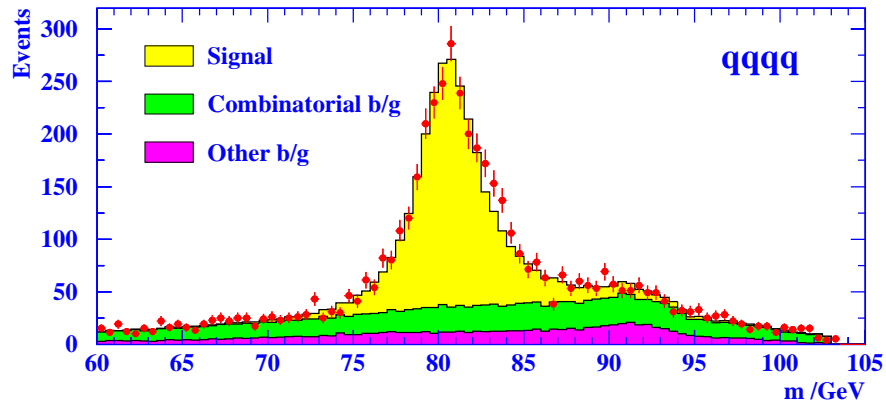
One W decays to a **charged lepton** and a **neutrino** the decays to **2 quarks**



Both Ws decay to a **2 quarks**

W Boson Mass

OPAL 183-209 GeV $\int L dt = 677 \text{ pb}^{-1}$

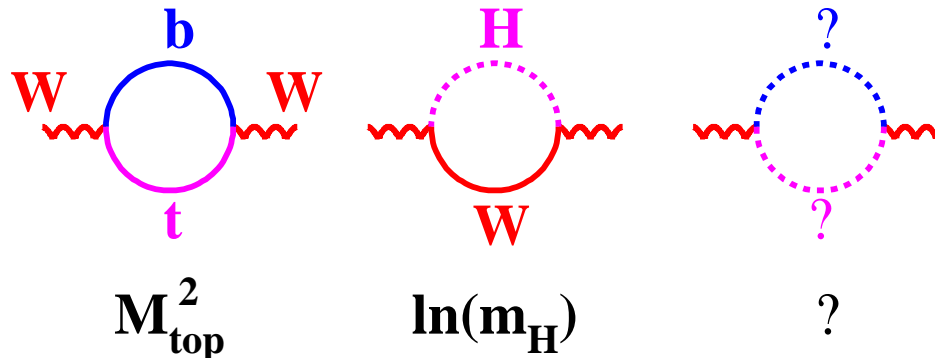


W boson mass measured
from the energy and
momentum of the
leptons and jets and

$$M_W = 80.42 \pm 0.05 \text{ GeV}/c^2$$

The power of precision

- In the Standard Model it is possible to calculate the W boson mass in terms of other measured quantities such as the Z mass
- BUT measured mass also sensitive to new particles via “loop corrections”



- HIGH precision measurements provide a probe of these corrections, e.g.
 - ★ in 1994 LEP measurements of M_Z gave a prediction that the top quark mass was about 175 GeV
 - ★ Later that year it was discovered at the Tevatron at Fermilab:
 - with a mass of 174 ± 5 GeV

The Higgs Boson

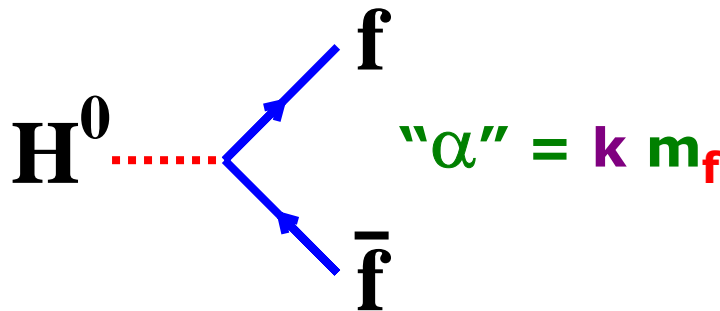
★ The is one final ingredient to the Standard Model
- the Higgs Boson

★ The Standard model as described so far is all very well
but it doesn't work for any particles with mass !

★ The **Higgs Boson** (which may/may not exist) fixes
this problem !

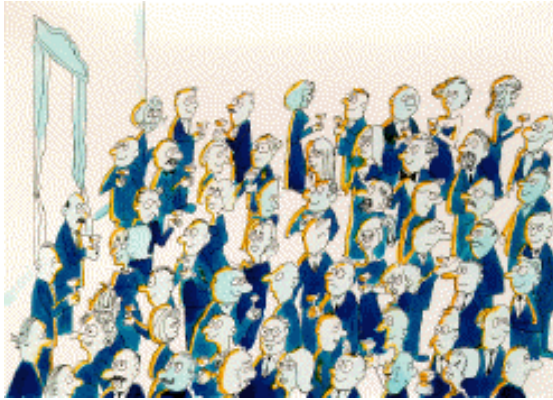
★ Unlike all other particles the "vacuum expectation
value" of the **Higgs Boson** is not zero –
"in the vacuum there are virtual Higgs bosons just
waiting to grab hold of any particle as it passes"

★ The interaction with the **Higgs Bosons** gives particles
mass



Coupling strength
proportional to mass

A nice analogy



- ★ In the houses of parliament there are always politicians present

(Higgs bosons have non-zero vacuum expectation value)



- ★ In walks the prime minister before entering the room (s)he can walk freely

(a massless particle)



- ★ The politicians gather around and he finds it difficult to move

(because of the interactions with the Higgs boson particles acquire mass)

A nice analogy... ..pushed too far



★ A rumour that the prime minister is about to resign is started



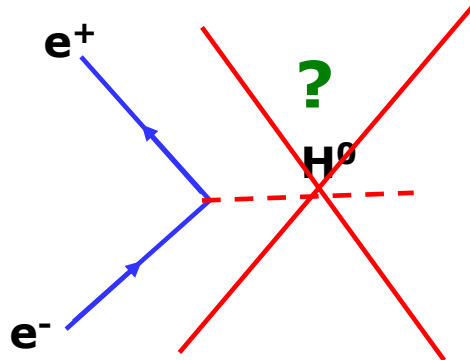
★ The politicians huddle together and now find it more difficult to move

(The Higgs bosons interactions with itself generates the Higgs boson mass)

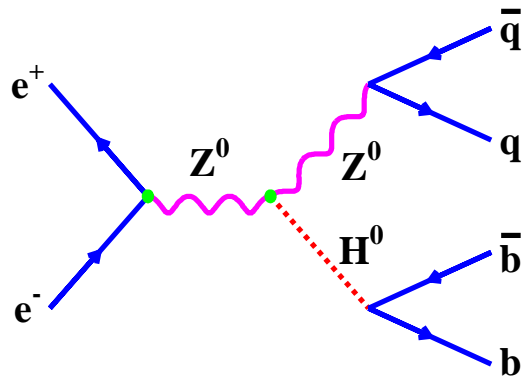
- In the same way as the top mass was predicted by the the precise measurements at LEP, these measurements predict that the Higgs mass is <200 GeV.
- Nice theory, but is there any evidence that the Higgs exists?

Searching for the Higgs at LEP

- ★ Recall the Higgs boson “couples” to mass
- ★ How can you produce the Higgs at LEP ($E = 200 \text{ GeV}$) and how would it decay?



The cross-section for this is very very small – why ?



Higgs couples to mass – so need to produce it from a massive particle + decays to the most massive particles allowed

- ★ Look for events with a Z and 2 jets from b-quarks
- ★ Hadrons with b-quarks decay via the weak interaction and live long enough to travel a few mm in our detectors! Identify b-quarks by “displaced vertices”

Was the Higgs seen at LEP ?

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

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, human beings 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 place in science history.

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 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 to create a coherent universe.

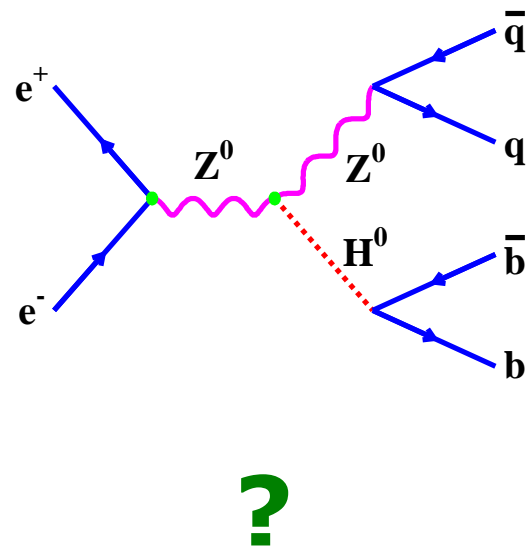
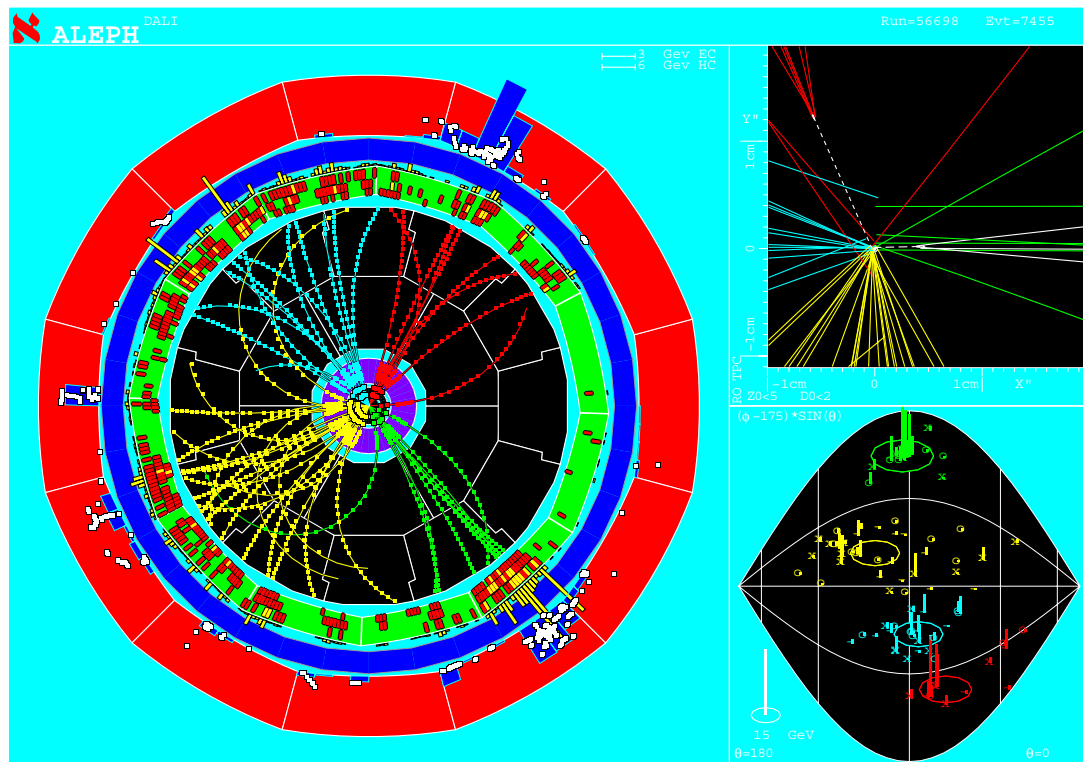
If, for example, the Higgs boson interacted with electrons slightly differently they would be too heavy for the elements vital for life to form.

This weekend Higgs was in contact with Cern in the hope his life's work had been proven a triumph. "After all this time I am delighted and relieved that we may finally be close to finding it," he said.

Jonathan Leake
Science Editor

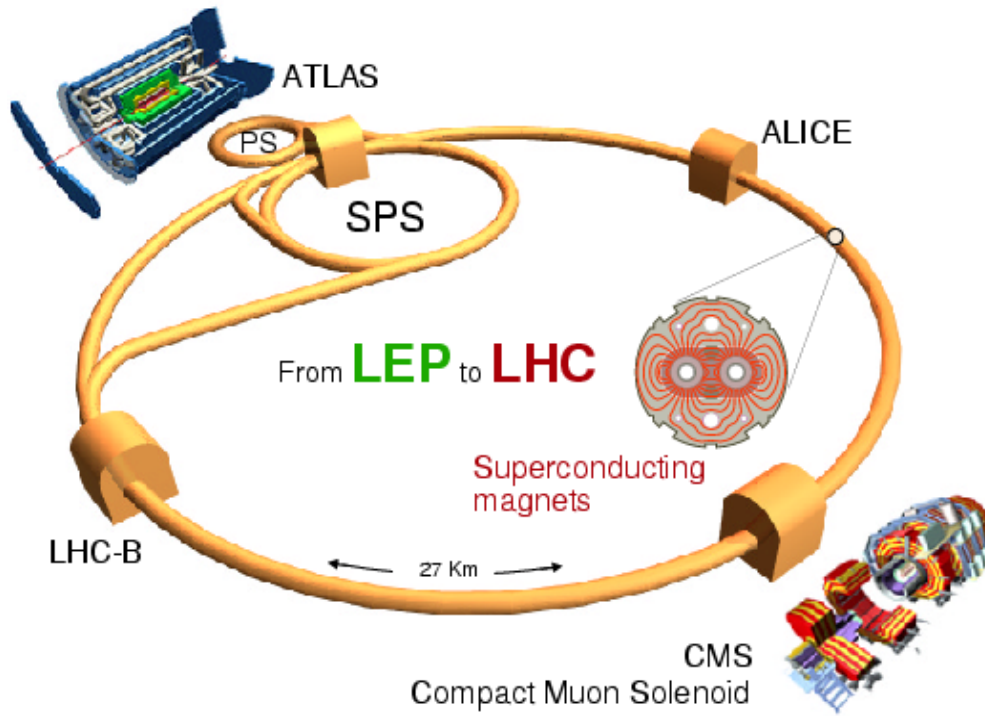
Sunday Times 10/9/2000

Higgs Production and Decay



- ★ The ALEPH experiment at LEP saw 4 events consistent with being $115 \text{ GeV}/c^2$ Higgs boson production
- ★ but not confirmed by the other experiments
 - the jury is still out !

Future Higgs Discovery ?



- LEP shut down in **2000**
- Its successor, the Large Hadron Collider (**LHC**) currently being built in the LEP tunnel
- If the Higgs exists it will be seen at the LHC
- due to start operating in **2008**
- if it exists – the Higgs will be discovered!



Matter and Forces

From first session :

Particle Physics is the study of

- ★ **MATTER** : the fundamental constituents which make up the universe
- ★ **FORCE** : the basic forces in nature, i.e. the forces between the fundamental particles

Try to categorise **PARTICLES** and **FORCES** in a simple and fundamental manner

So where are we now?

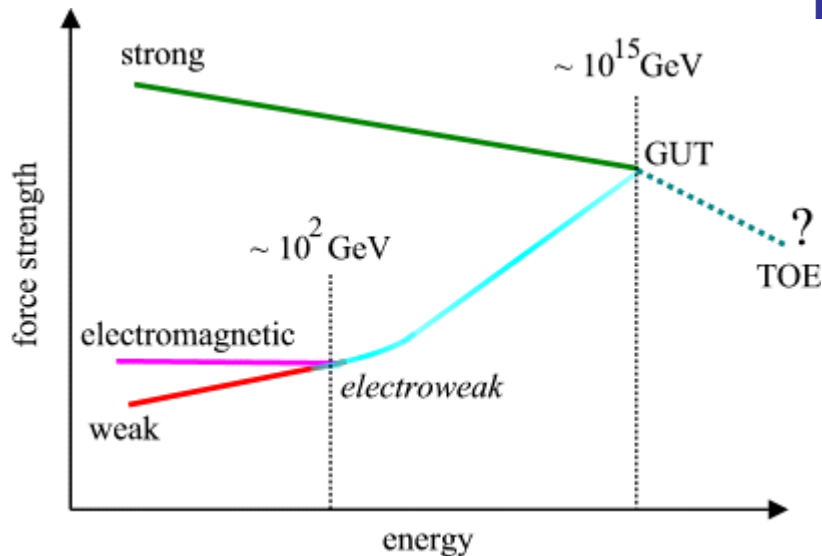
FORCES : Unification

1860 : Maxwell unified theory of Electricity and magnetism

1970- : Glashow, Salam, Weinberg unified theory of Electromagnetism and Weak interaction

????? : What next ?

Recall strength of interaction “RUNS”

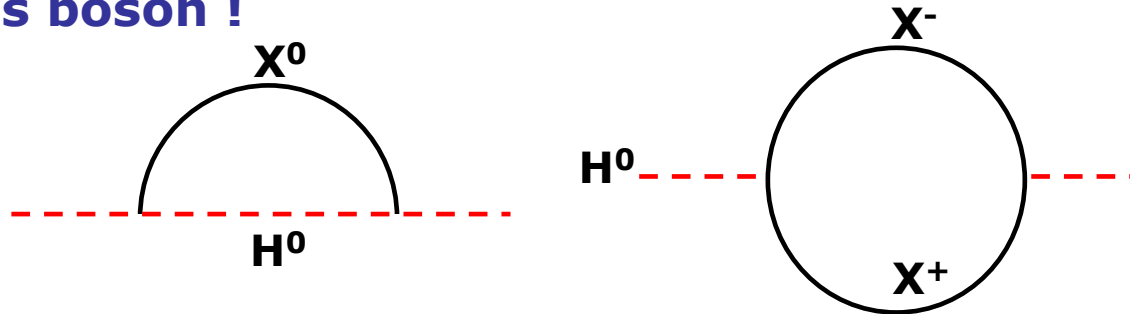


As energy increases:

- ★ **Electroweak gets stronger**
- ★ **QCD gets weaker**
- ★ **At some point – all forces have same strength !**

Higgs mass and SUSY

- ★ The Higgs boson “couples” to mass
- ★ This is problematic
- ★ Any very massive particle that exist (i.e. way beyond the energies of current accelerators) adds mass to the Higgs boson !



- ★ The Higgs boson mass should be very large ! Not consistent we LEP data
- ★ A possible solution: Supersymmetry (SUSY)
- ★ For every standard model particle there is also a SUSY partner (with different spin)
- ★ e.g. Spin-half electron \rightarrow spin-1 selectron e
- ★ This solves the problem with the Higgs mass – SUSY particle loop cancels the SM particle loop \sim
- ★ **BUT:** (more than) doubles number of “fundamental particles”
+to date : no experimental evidence for SUSY

Matter : **what is the matter ?**

- ★ Many reasons to believe that a large fraction of the matter in the universe is not made up of the known particles



+

DARK MATTER

- ★ We don't yet know what is this nature of the dark matter
- ★ Supersymmetry offers a possible solution
- ★ The **lightest** SUSY particle could make up the dark matter

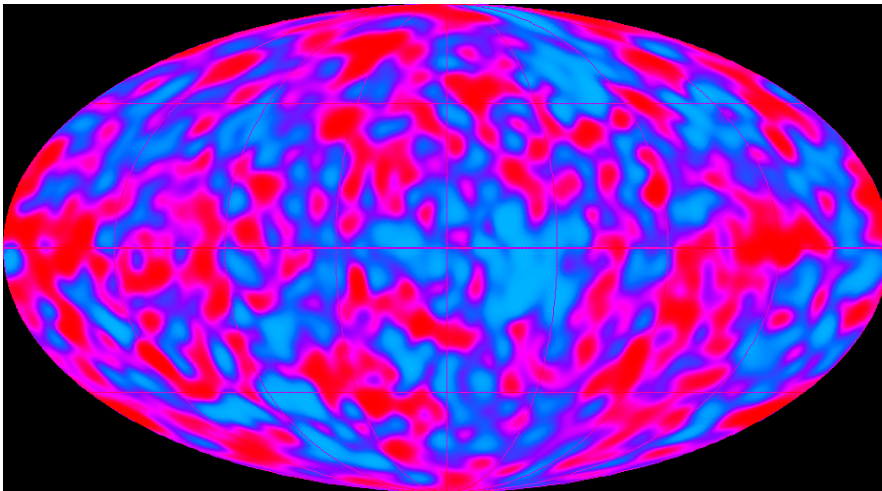
BUT, also a problem with the ordinary (baryonic) matter....

Another Problem : Matter in the Universe



$\sim 10^{80}$ protons

~ 0 antiprotons



$\sim 10^9$ photons for every proton

How did this happen ?

- **Approximately 0.001 seconds after Big Bang:**
 - the universe was a “hot expanding soup” of :

e^- , e^+ , p , \bar{p} , n , \bar{n}

But for some reason there was a small excess of particles e.g. for every

10^9 anti-protons

$10^9 + 1$ protons

After annihilation

2×10^9 photons

1 proton

0 anti-protons

**Due to matter and anti-matter behaving in a Slightly different manner..... not yet understood !
Cannot be accounted for by the Standard model**

★ One of many remaining mysteries.....

Conclusion

Successes of the Standard Model

- ★ The Standard Model describes **ALL** experimental data
- ★ All particles in the Standard Model except the **Higgs** have been observed
- ★ Predictions tested to very high precision – **it works !**

Questions/Problems with the Standard Model

- ★ The Standard Model is just that “a model”
 - many parameters, e.g. masses, couplings,....
- ★ Why do the particles have the masses they do ?
- ★ Why 3 generations ?
- ★ Are the quarks/leptons really fundamental ?
- ★ Only just beginning to understand neutrinos
- ★ Why didn't all the matter and anti-matter annihilate ?
- ★ Need to unify **all** forces – including **GRAVITY**
- + Dark matter + many more

Our understanding of particle physics is still evolving.
Over the next few years many new experiments and
hopefully some surprises