An Introduction to Modern Particle Physics

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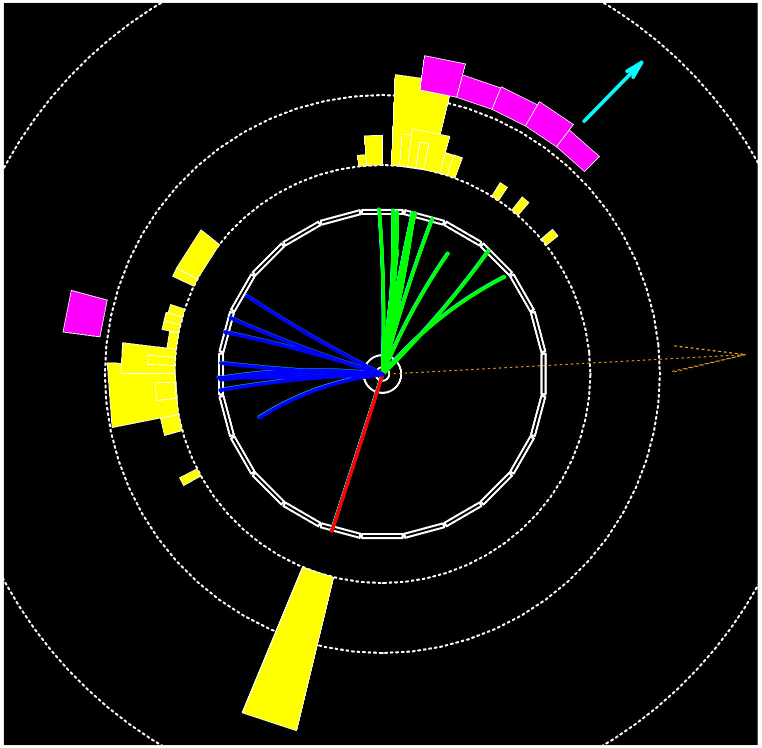


Science Summer School: 30th July - 1st August 2007

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

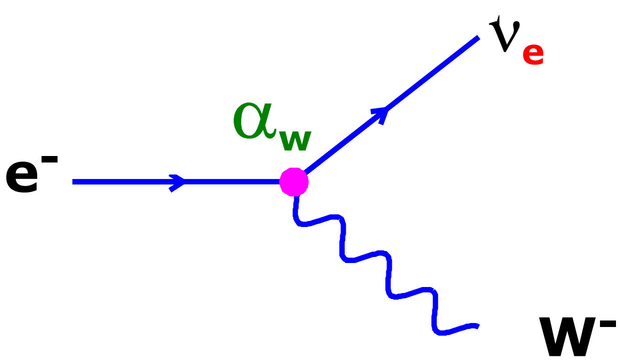
★ **The Weak interaction**
- W bosons
- Neutrinos and Neutrino Oscillations
- The MINOS Experiment

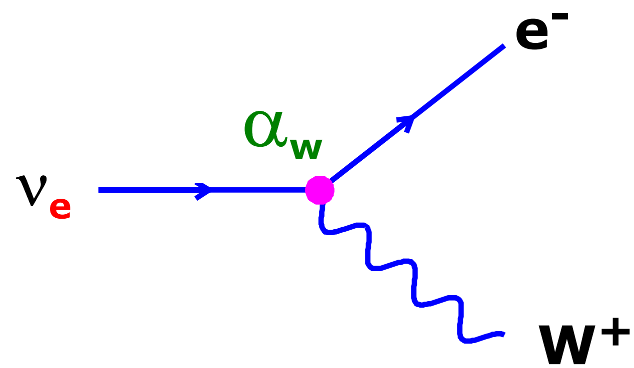
★ **The Standard Model (what we know) and beyond**
- Electroweak Unification
- the Z boson
- the Higgs Boson
- Dark matter and supersymmetry
- Unanswered questions

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 !**

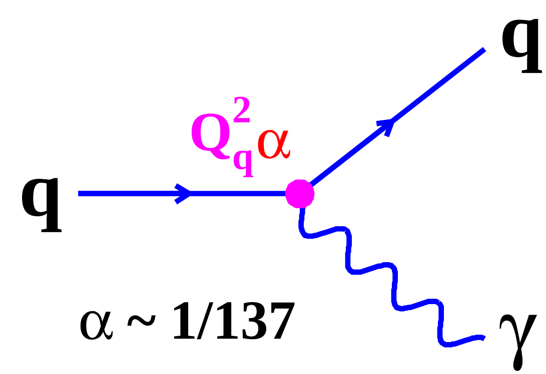
★ **Suggestive of UNIFICATION OF FORCES**

★ **Only weak because need a lot of energy to “make” a W-boson (recall easier to emit low energy virtual particles)**

Recap

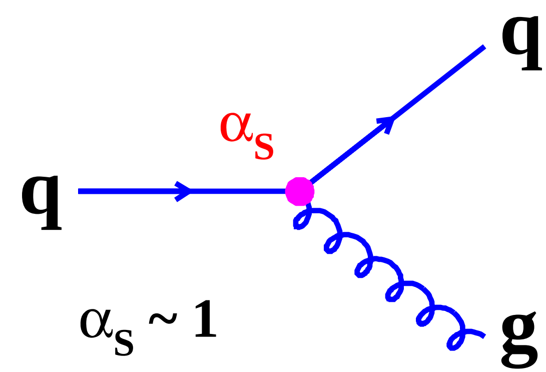
Electromagnetic Interaction:

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



Strong Interaction:

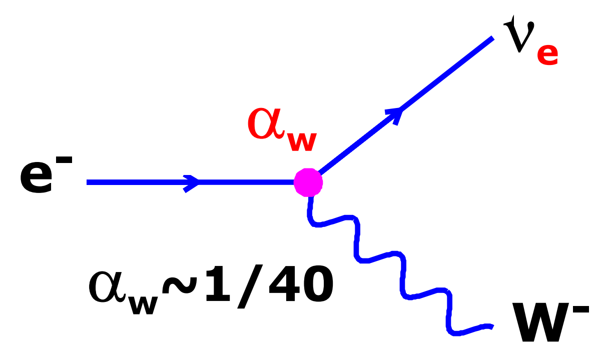
- ★ Mediated by massless GLUONS
- ★ GLUON couples to “COLOUR” charge
- ★ Does not change flavour
- ★ QUARKS/GLUONS



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

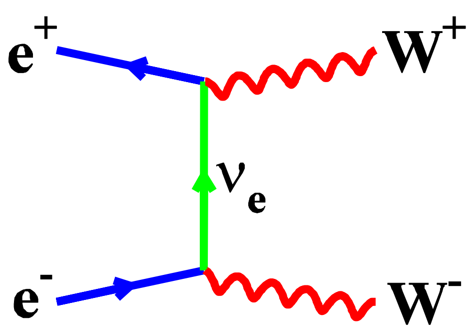
  $M_W \sim 80$ GeV/c^2



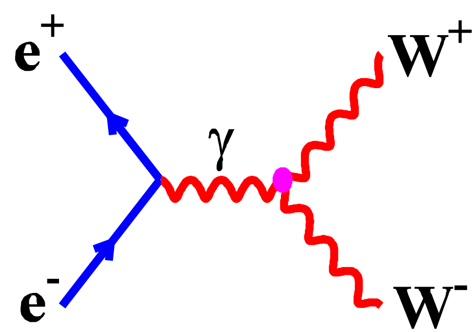
Electroweak Unification

Hints for Unification of WEAK and EM forces:

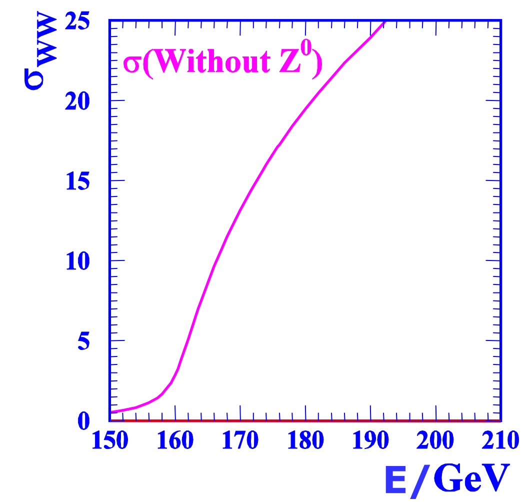
- Strengths of **WEAK** and **EM** interactions are similar
- Force carrying particle of the **WEAK** force **is charged** **i.e.** carries charge of the EM interaction
- also consider $e^+e^- \rightarrow W^+W^-$ – 2 ways this can occur



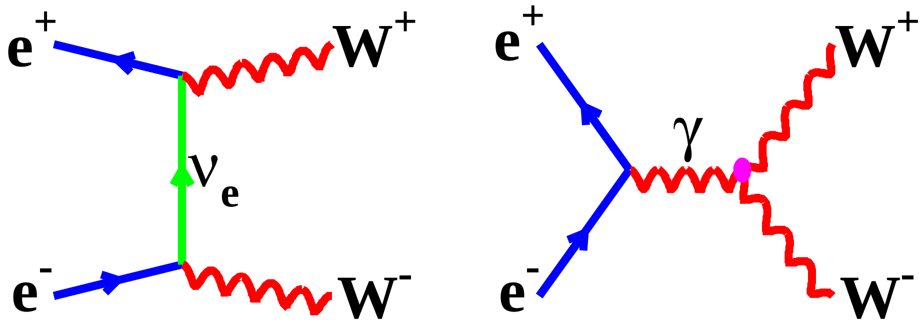
PURE WEAK

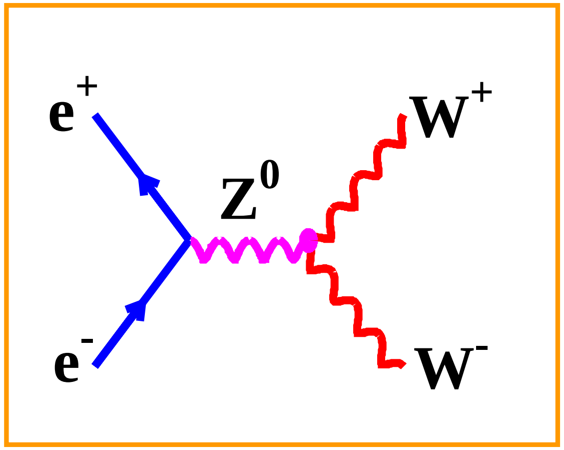


PURE EM

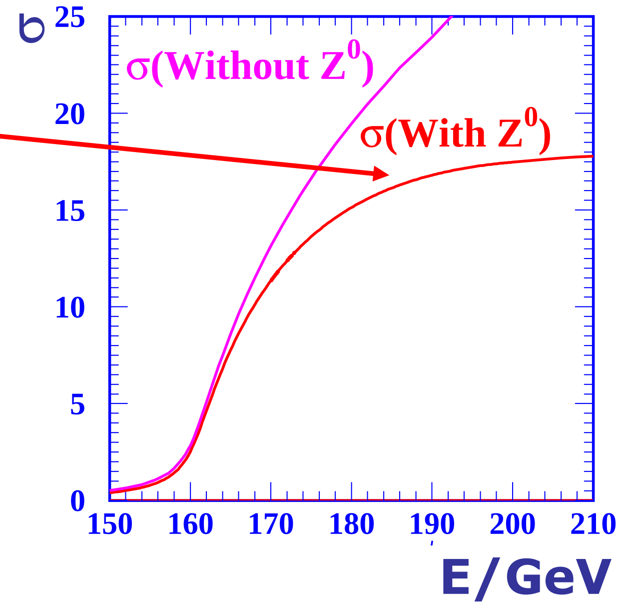


- Cross-section goes to infinity at high energies
- Problem fixed by assuming another process





This prevents the cross-section increasing without limit !



★ BUT only works of 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

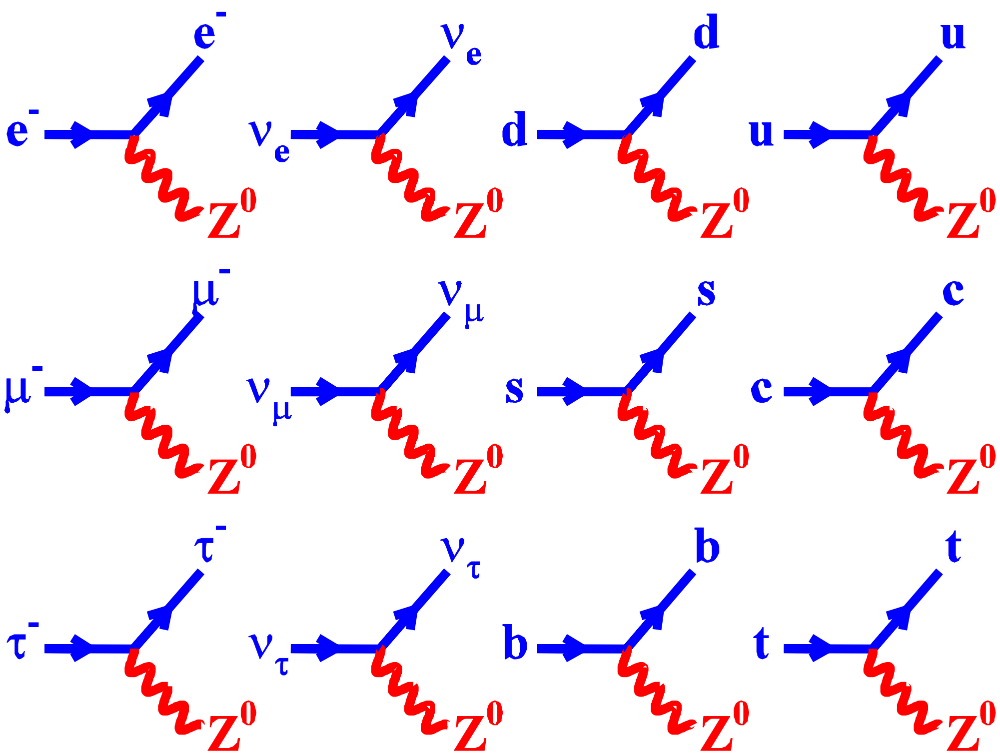
★ Z^0 "acts like a neutral W-boson"

★ 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 ~ 90 GeV/c^2 ➡ 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 (d)	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 GeV
  $e^+e^- \rightarrow Z \rightarrow$
- ★ 16 million Zs detected
- ★ 1996-2000 $E > 2M_W c^2$
  $e^+e^- \rightarrow W^+W^- \rightarrow$
- ★ 30,000 W^+W^- detected

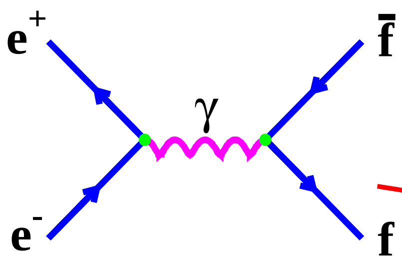
- Main emphasis on making very precise measurements of the properties of the Z and the W
- In the Standard Model if you know e.g.

  α , α_w, M_w can predict <u>exactly</u> M_z

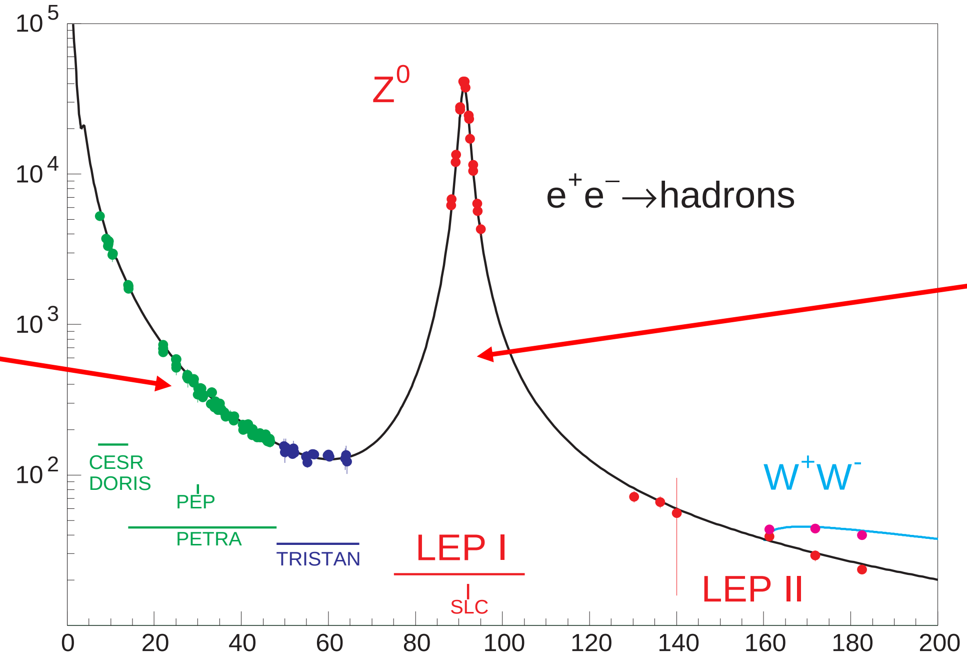
- **Make precise measurements to test predictions of Standard Model**

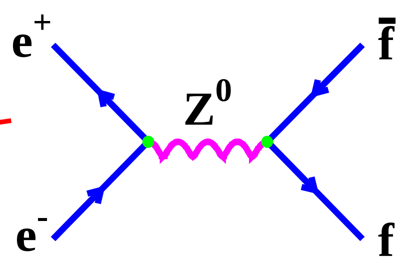
e^+e^- annihilation at the Z

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



Here f is any charged particle

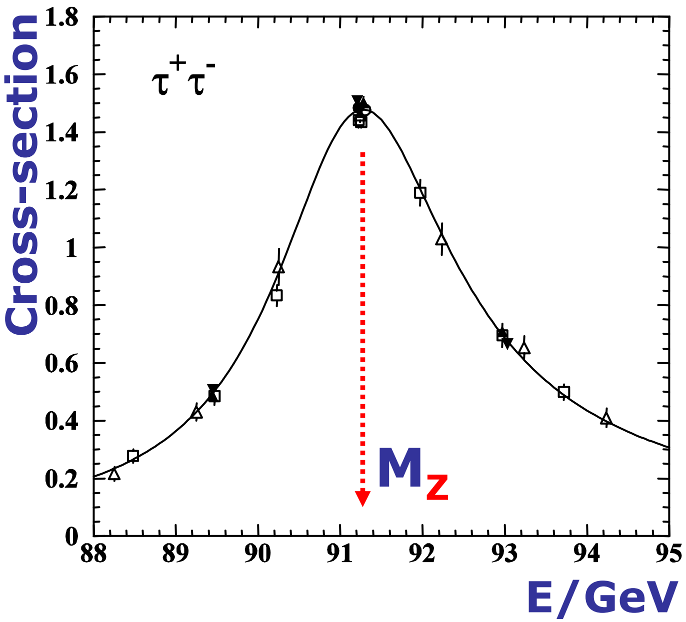




Here f is any particle

- ★ 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

Measuring the Z Mass



Simple method:

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

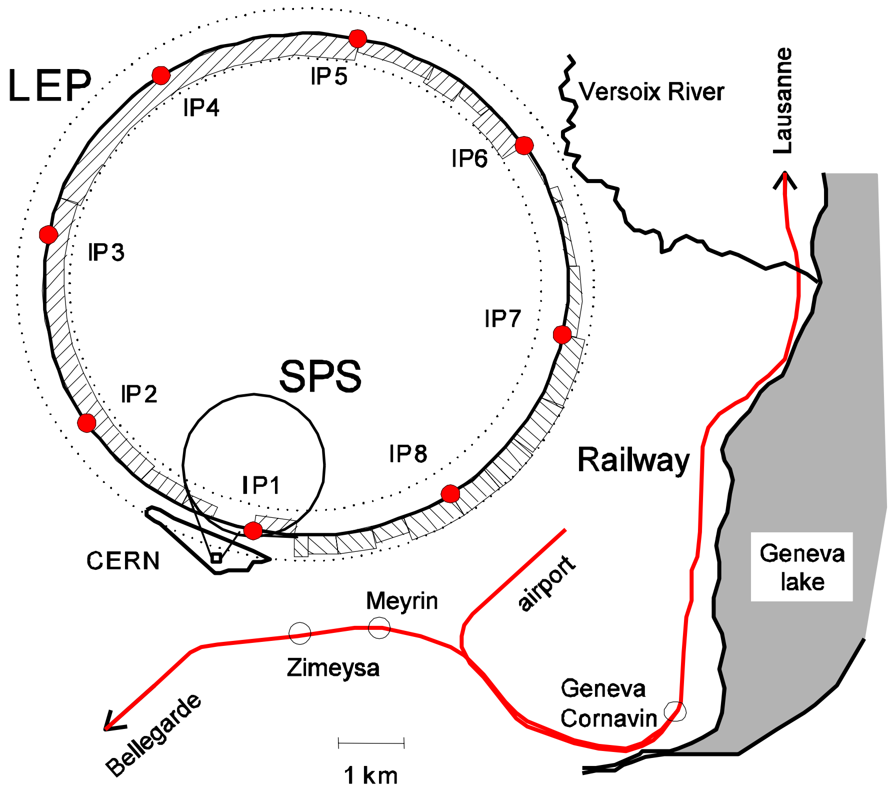
M_Z = 91.1875±0.0021 GeV/c^2

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

Simple method – but in practice very hard !

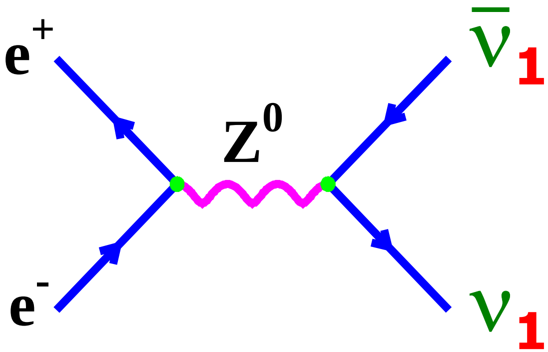
- As the moon orbits the Earth it distorts the rock in the Geneva area very very slightly !
- The nominal radius of the accelerator of 4.3 km varies by ±0.15 mm enough to ruin the measurement
- therefore need to correct for tidal effects !

- **Also need a train timetable !**



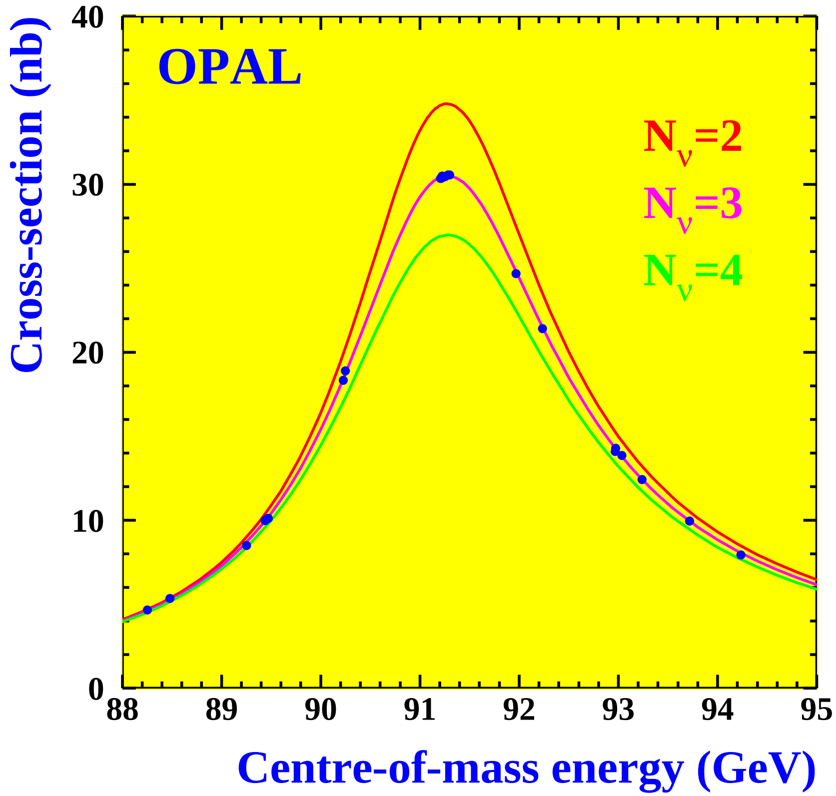
Leakage currents from the TGV rail via lake Geneva follow the path of least resistance using the LEP ring as a conductor. Everytime a train passes by the LEP beam energy changed very slightly

Number of Generations



★ Z can "decay" into all particle types provided $M_Z > 2\,m$

★ Even though you don't observe $e^+e^- \rightarrow \nu\,\nu$ it does affect the shape of the peak



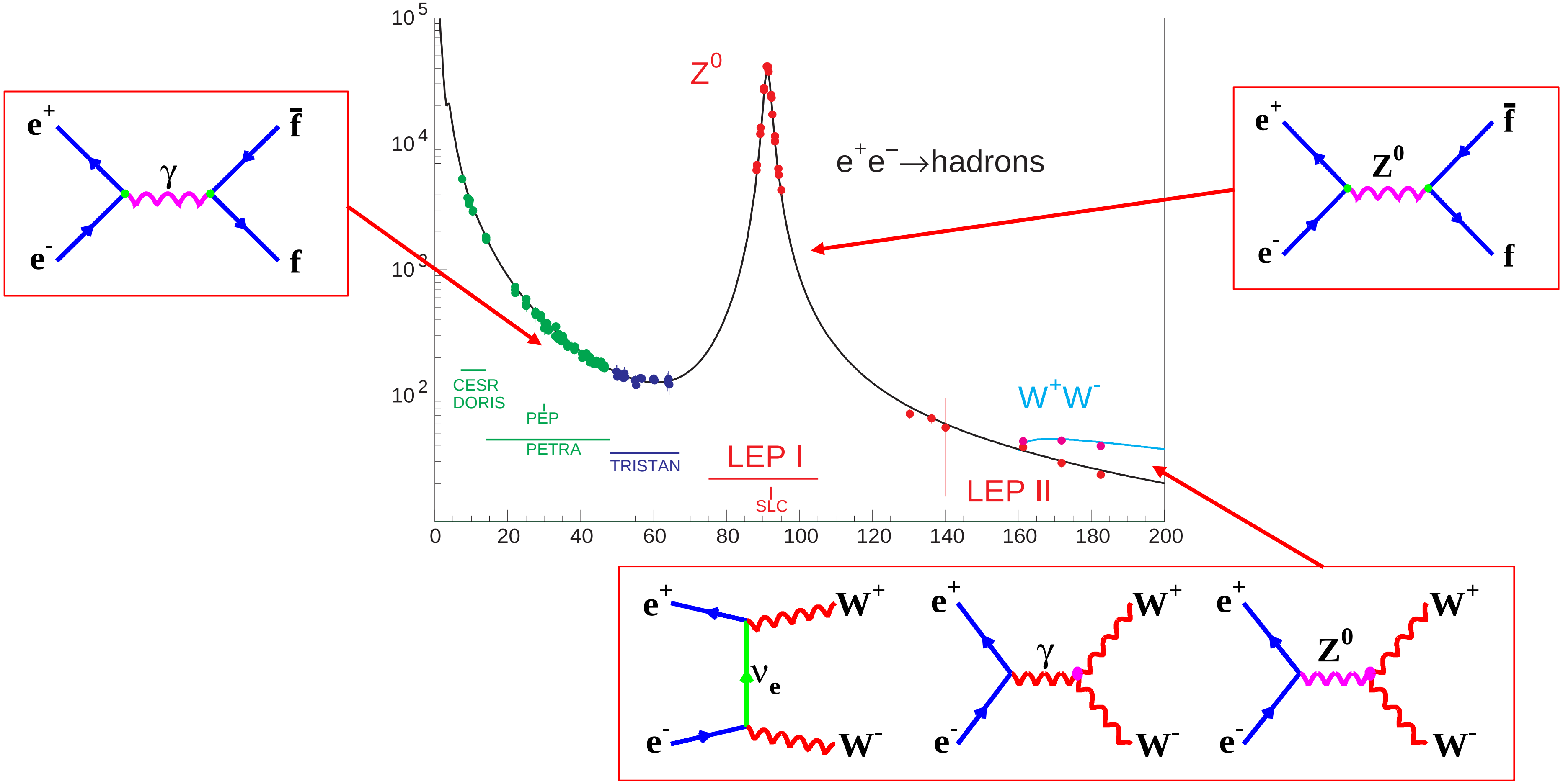
3 GENERATIONS OF NEUTRINO

★ This is why we believe there are only 3 generations !

★ Don't understand <u>why</u> there are 3 generations !

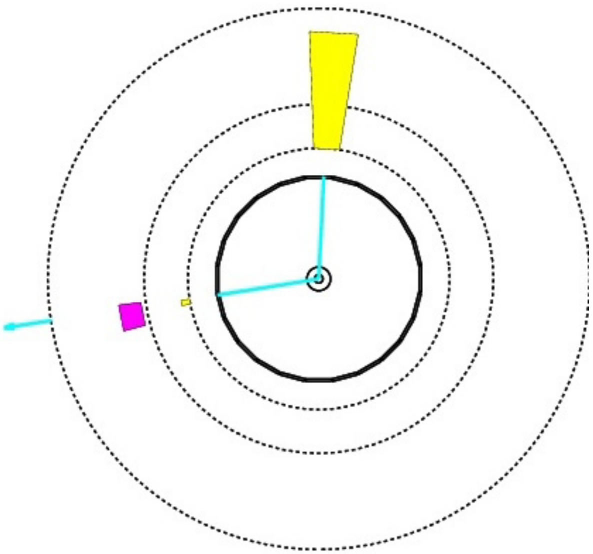
$e^+e^- \rightarrow W^+W^-$

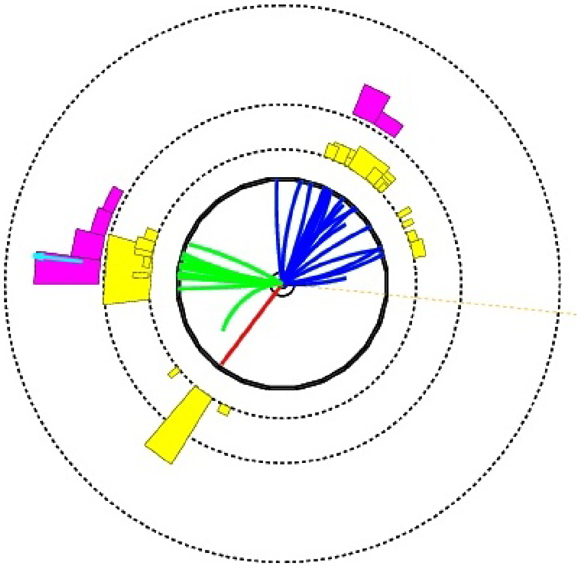
★ Above the Z peak, produce pairs of W bosons when $E > 2M_W$, i.e. $E > 160$ GeV

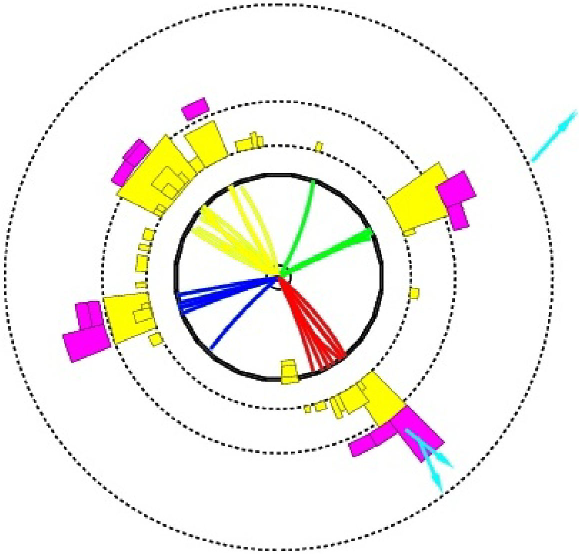


W Decay

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





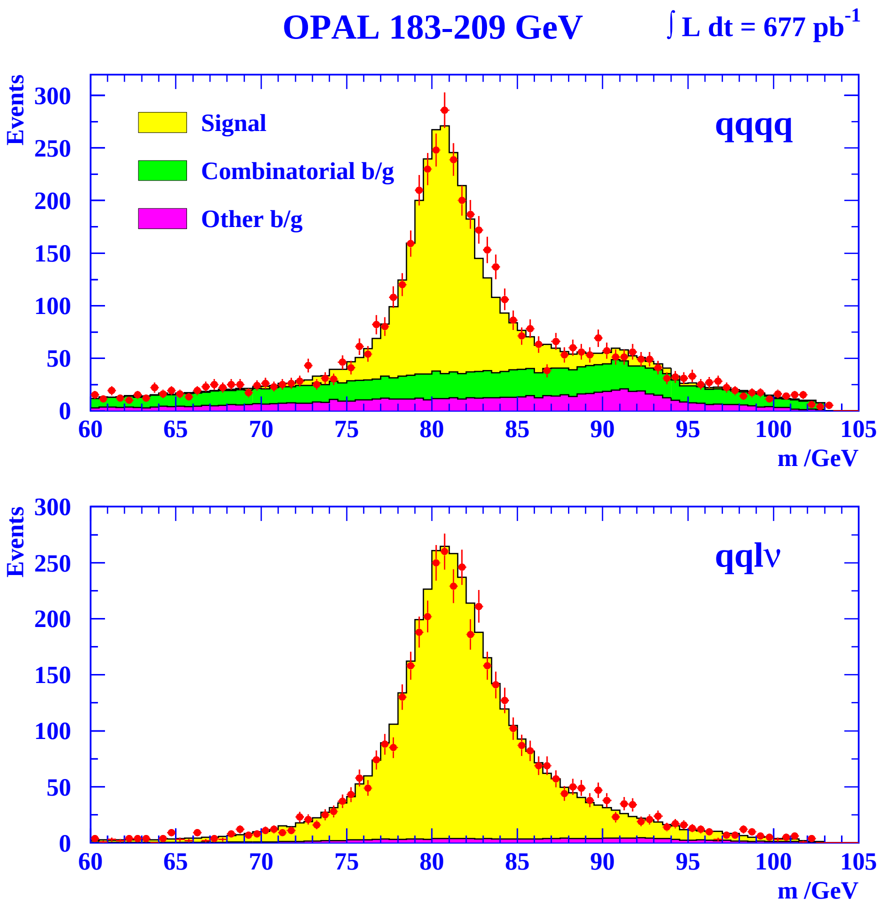


Both Ws decay to a charged lepton and a neutrino

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

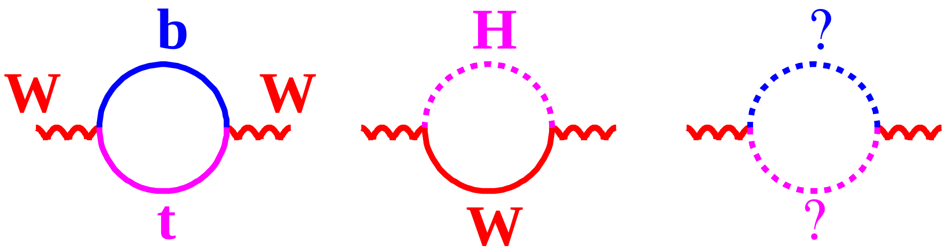


W boson mass measured from by the energy a momentum of the leptons and jets and

M_W = 80.42±0.05 GeV/c²

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"



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

- 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

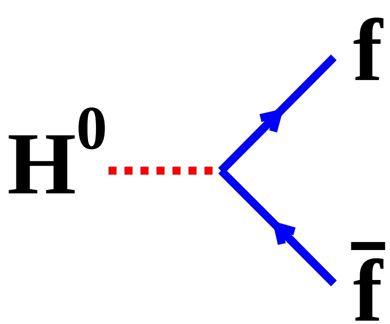
★ The is one final ingredient to the Standard Model
- **the Higgs Boson**

★ 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"

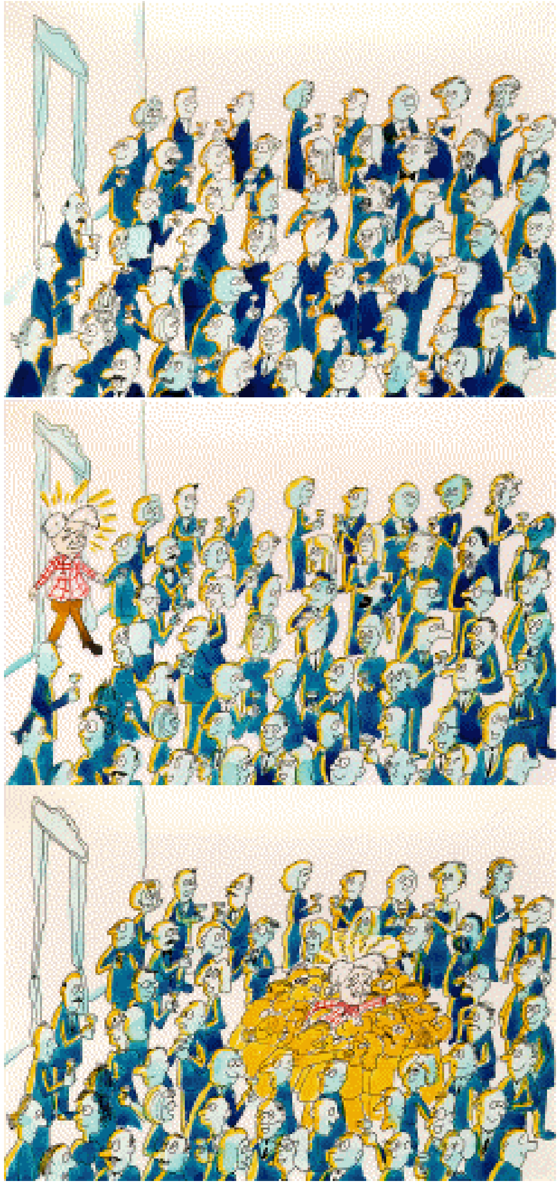
★ The interaction with the **Higgs Bosons** gives particles mass



"α" = $k\, m_f$

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

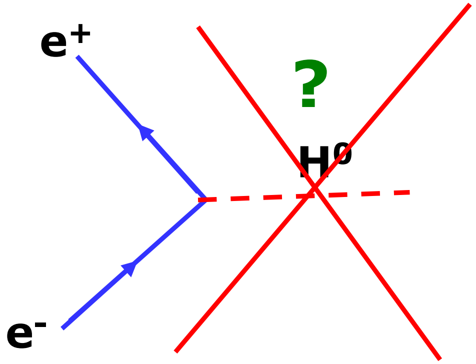
★ The politicians huddle together and now find it more difficult to move

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

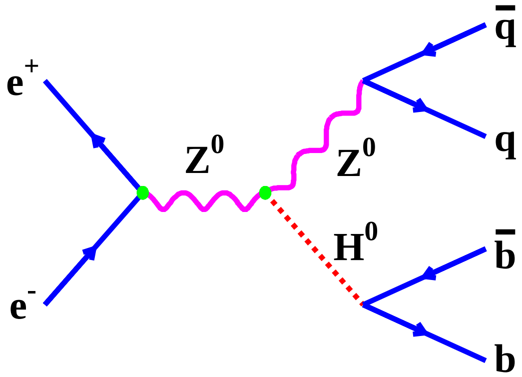
- In the same way as the top mass was predicted by the the precise measurements at LEP, these measurements predict that the Higgs mass is <200 GeV.
- Nice theory, but is there any evidence that the Higgs exists?

Searching for the Higgs at LEP

- ★ Recall the Higgs boson "couples" to mass
- ★ How can you produce the Higgs at LEP (E= 200 GeV) and how would it decay?



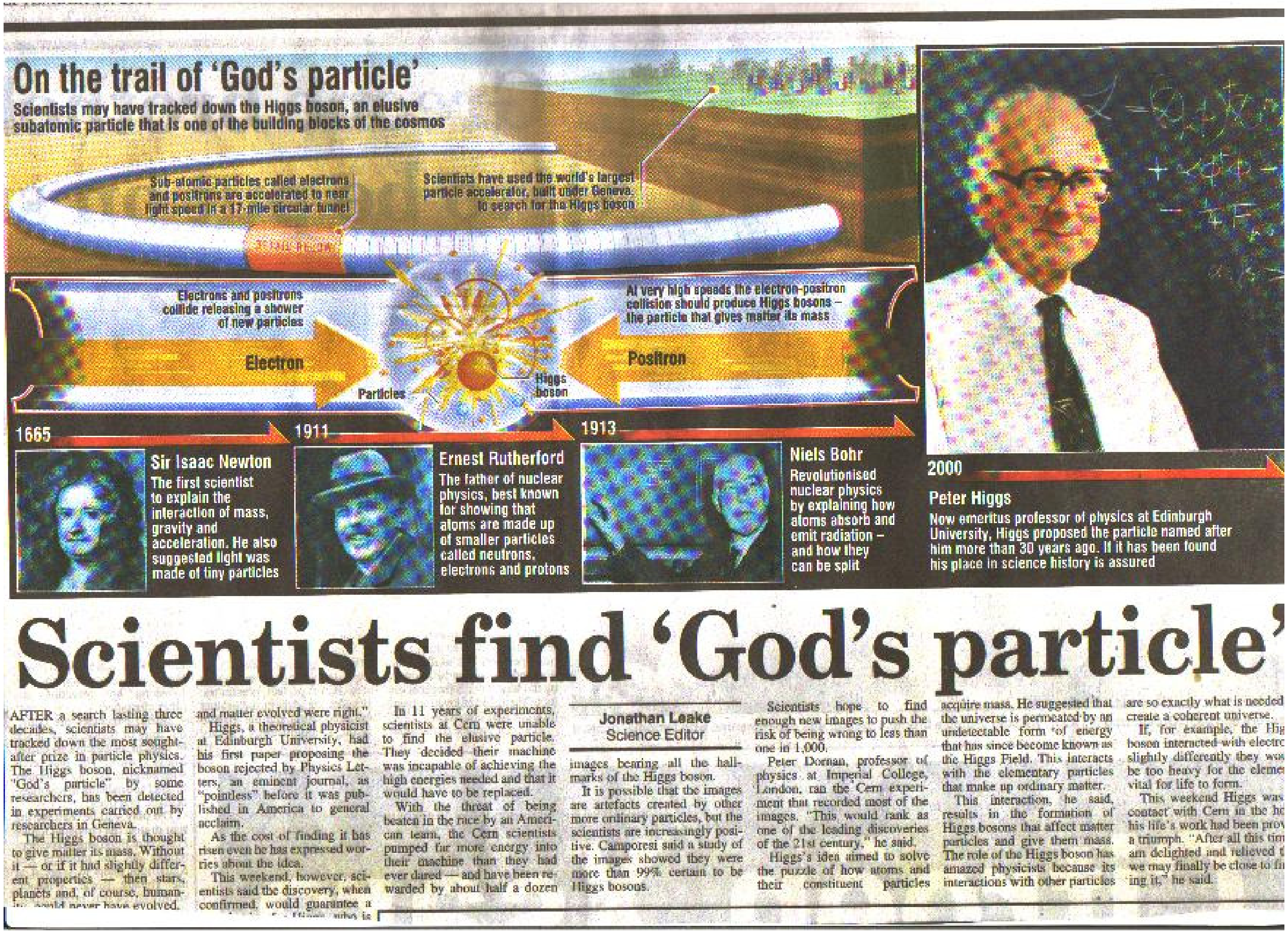
The cross-section for this is is very very small – why ?



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

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

Electron

Positron

Particles

Higgs boson

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'

Jonathan Leake
Science Editor

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 ... 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 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.

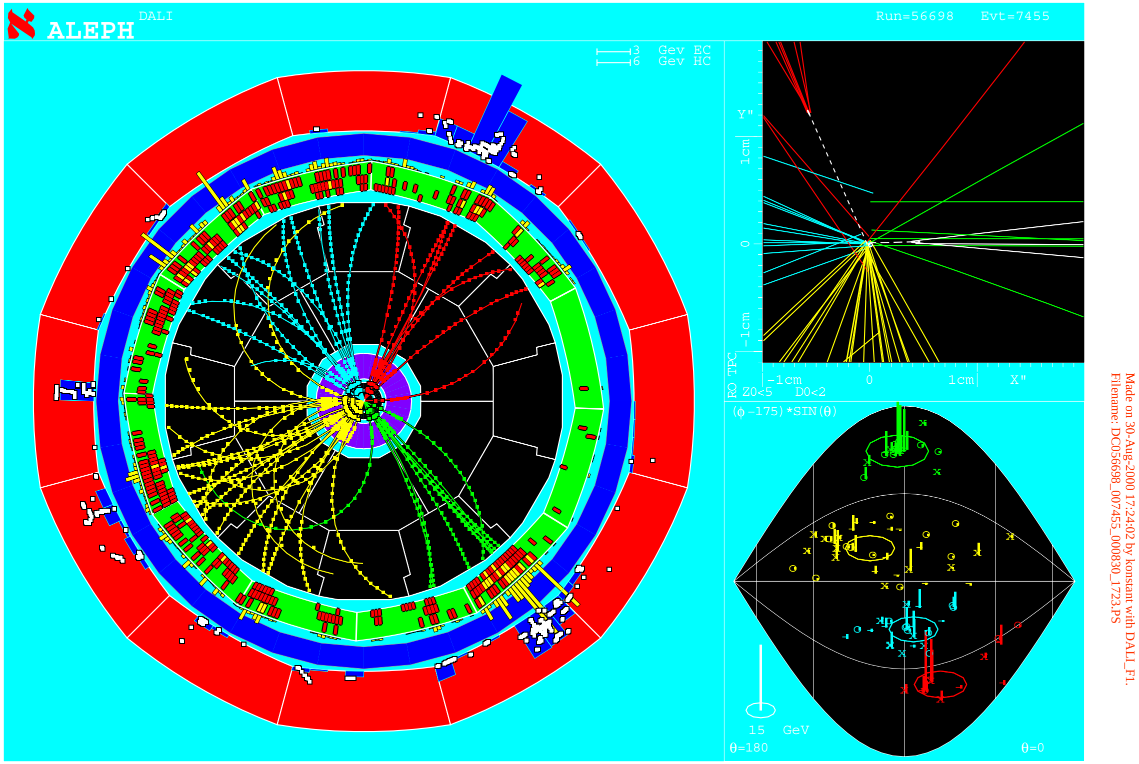
This interaction, he said, results in the formation of Higgs bosons that affect matter particles and give them mass. The role of the Higgs boson has amazed physicists because its interactions with other particles are so exactly what is needed create a coherent universe.

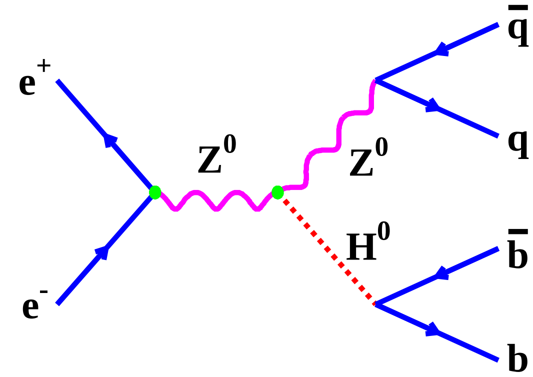
If, for example, the Hig... boson interacted with electro... slightly differently they wo... be too heavy for the eleme... vital for life to form.

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.

Sunday Times 10/9/2000

Higgs Production and Decay





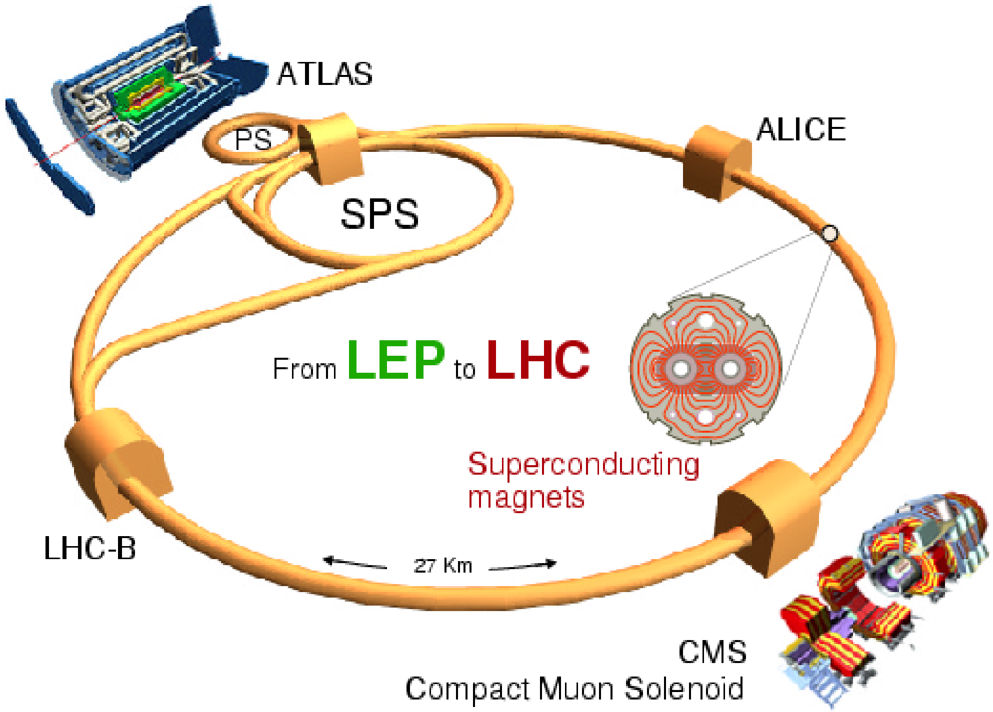
?

★The ALEPH experiment at LEP saw 4 events consistent with being 115 GeV/c² 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!

p → ← p

E ~ 14000 GeV

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

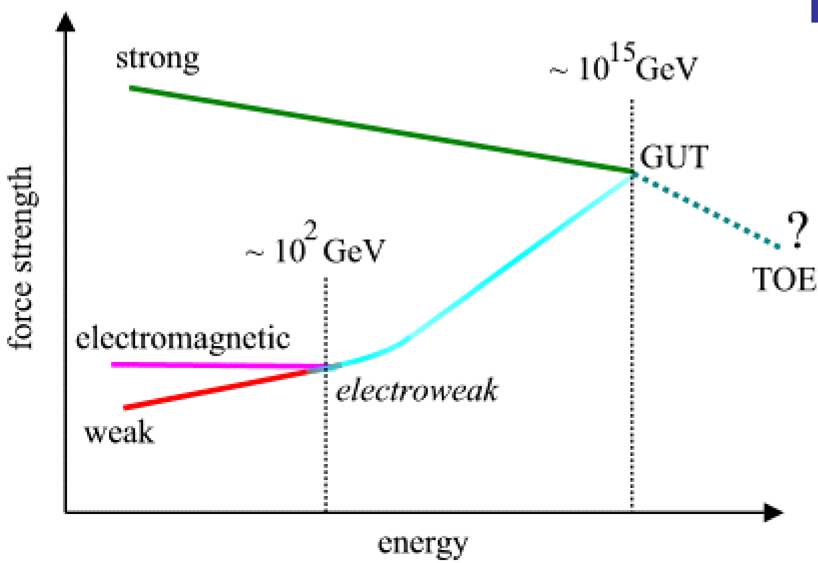
So where are we now?

FORCES : Unification

1860 : Maxwell unified theory of Electricity and magnetism

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

????? : What next ?



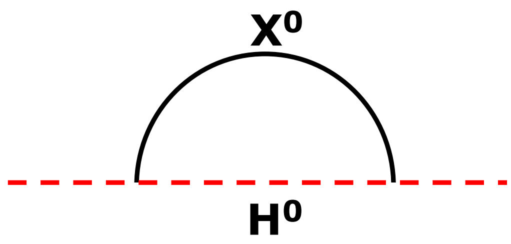
Recall strength of interaction "RUNS"

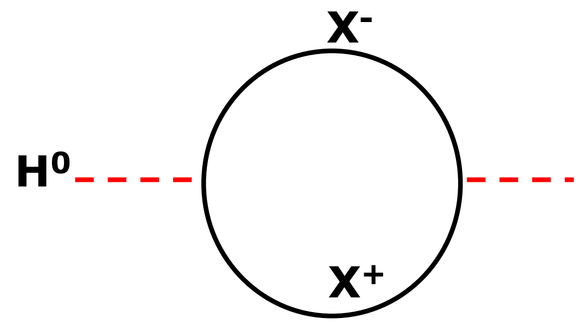
<u>As energy increases:</u>

- ★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 → spin-1 selectron $\tilde{e}$
- ★ This solves the problem with the Higgs mass – SUSY particle loop cancels the SM particle loop
- ★ **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

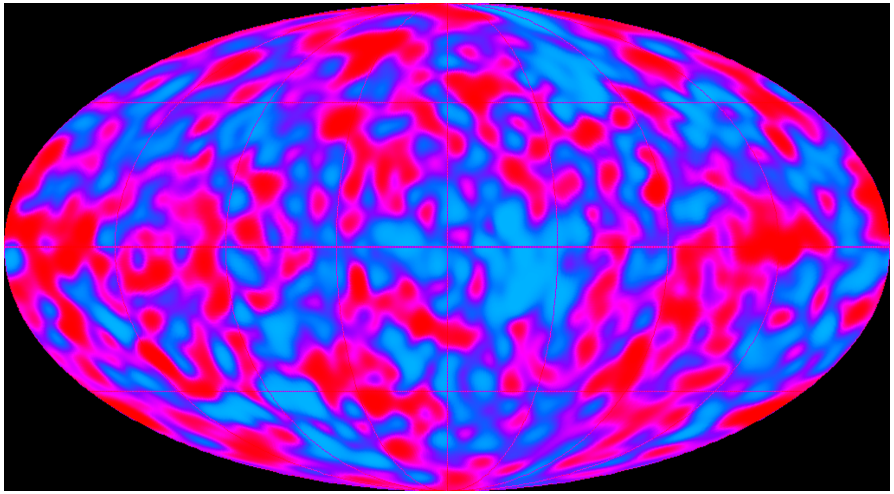
+ **DARK MATTER**

★ 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

~ 10^{80} protons
~ 0 antiprotons



~ 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 <u>except</u> 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