Introduction to the Standard Model

Quarks and leptons

Bosons and forces

The Higgs

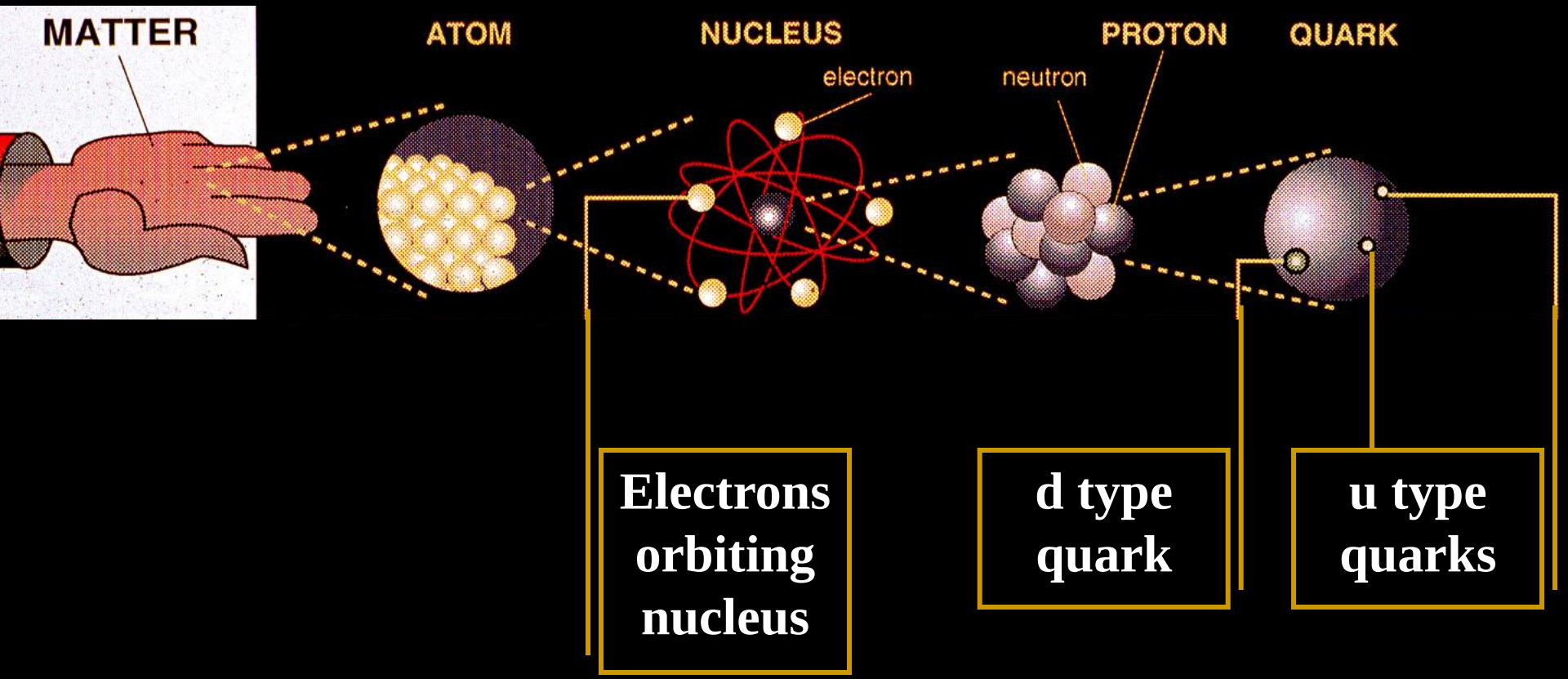
Bill Murray,
RAL,

March 2002

Outline:

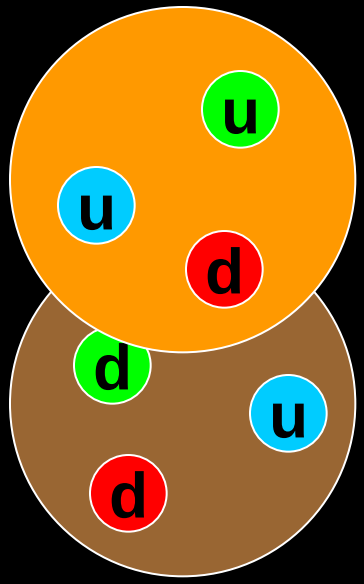
- An introduction to particle physics
- What is the Higgs Boson?
- Some unanswered questions

From you to the quark



The Matter Particles

Proton



Mass: 1.7 10^{-27} kg
charge: +1

Neutron

Charge: 0

Electron

e

Mass: 0.0005 proton mass
charge: -1

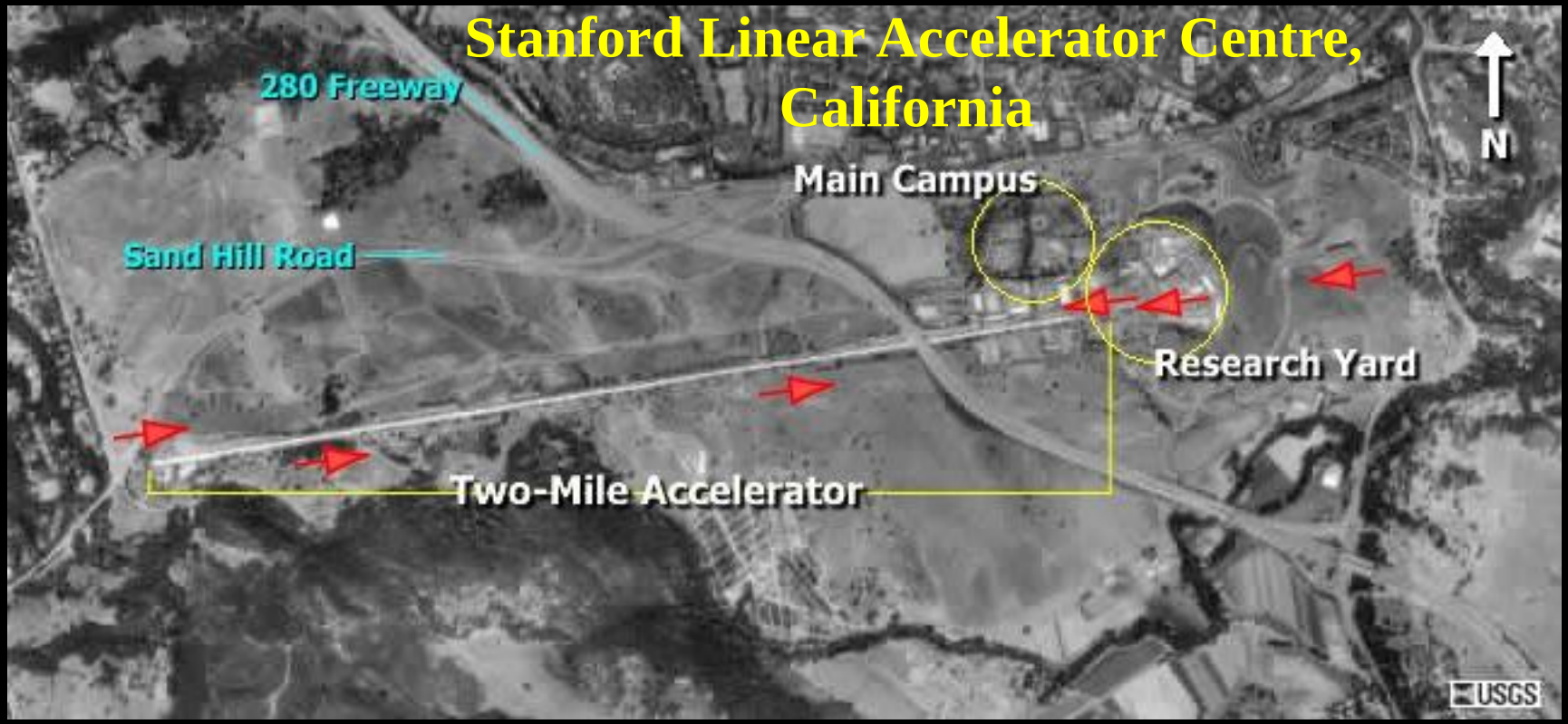
Neutrino

ν

Mass: ~<10^{-9} proton mass?
Charge: 0

How do we know about quarks?

Rutherford found a nucleus in the atom by firing alpha particles at gold and seeing them bounce back



Fire electrons at protons: See big deflections!

Late 1960's

The particles of Matter

‘up’ quark

‘down’ quark

neutrino

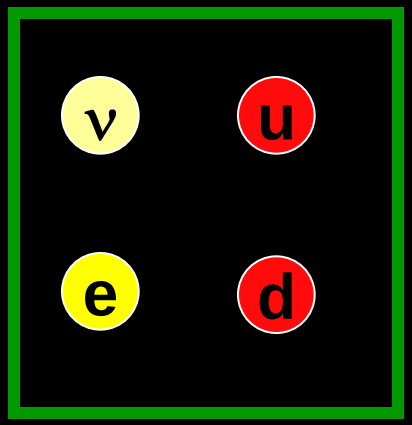
Electron

Why 3 colours?

Come in 3 versions, known as colours

Exercise to check this later

The particles of Matter

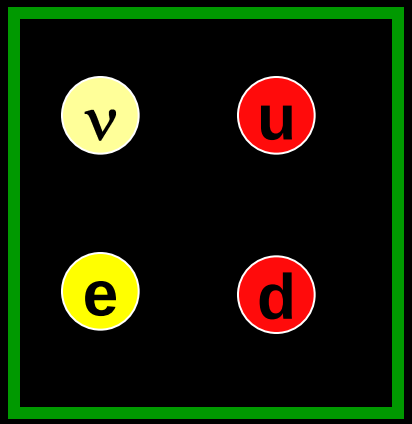


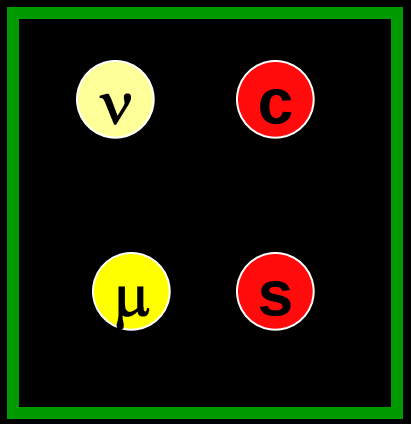
All ordinary matter is composed of these

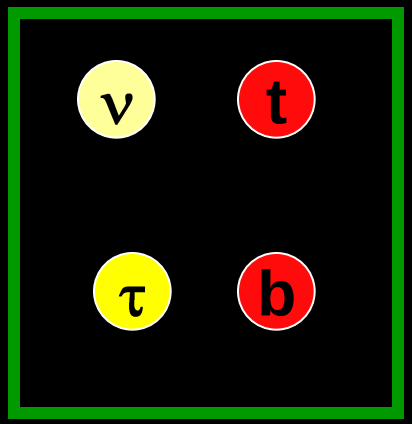
(There is a corresponding antiparticle for each)

See Stefania's talk later

The Matter particles







1st Generation

Ordinary matter

2nd Generation

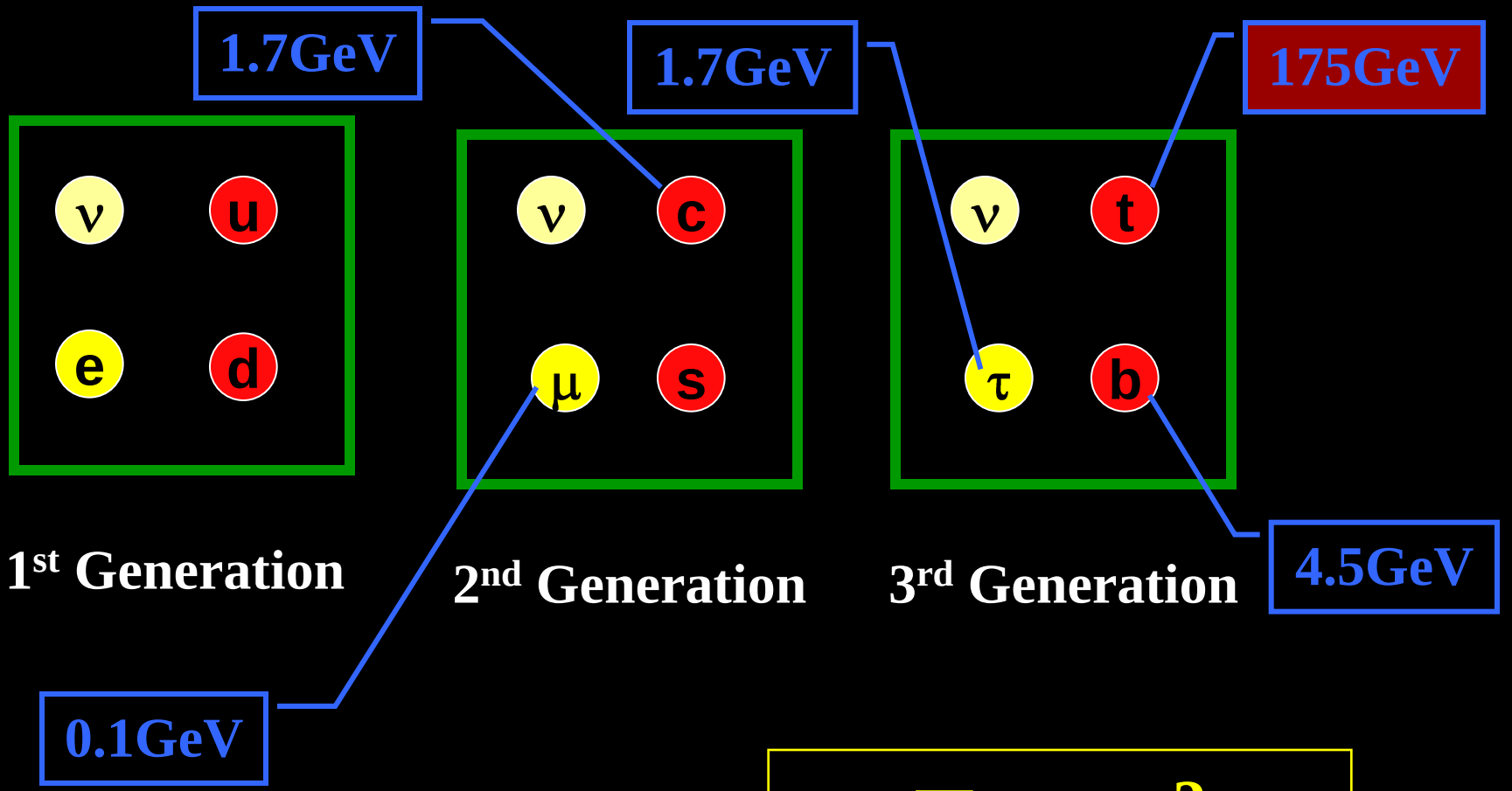
Cosmic rays

3rd Generation

Accelerators

Why 3 generations ?

The Matter particles

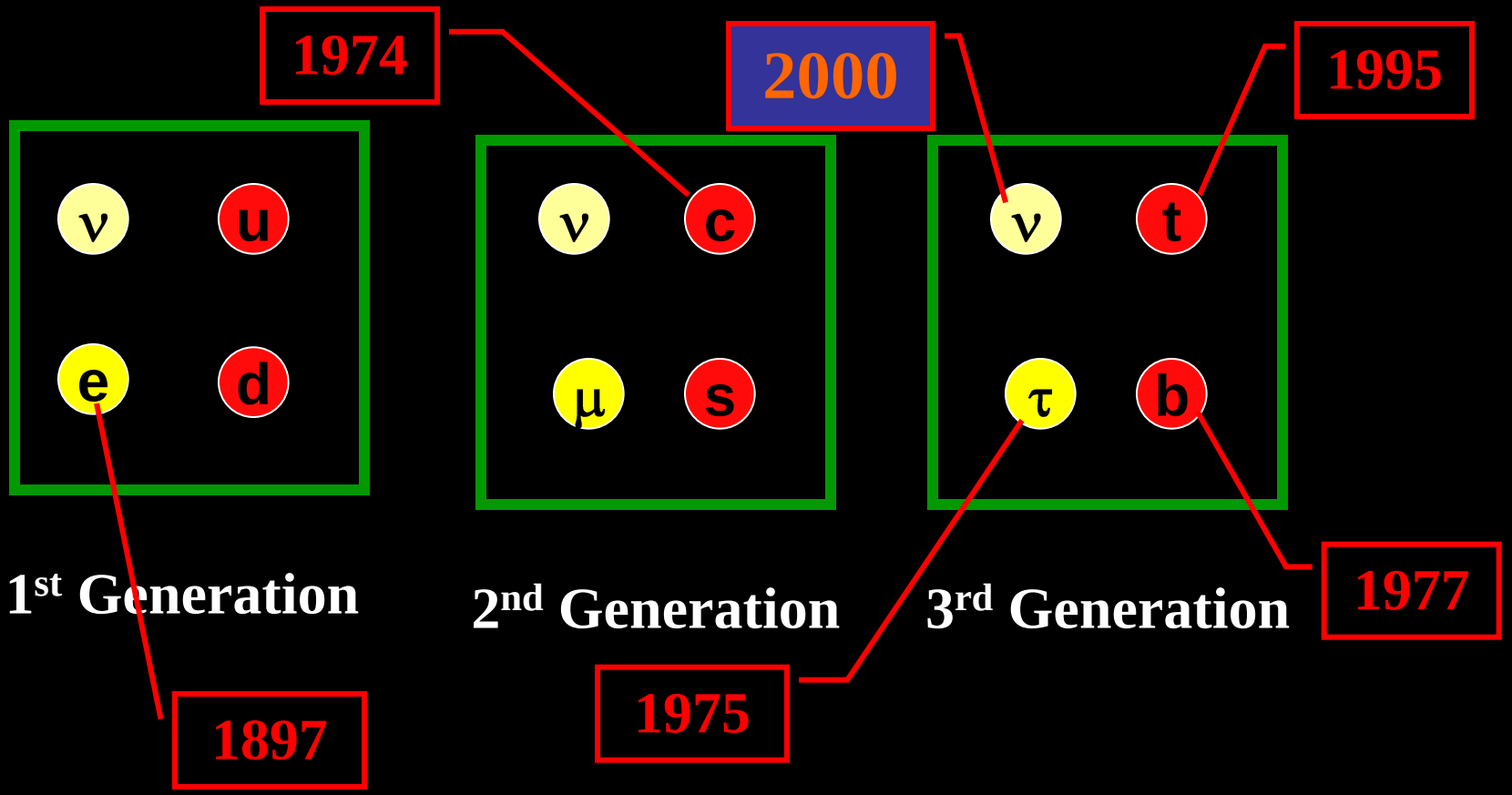


Others are lighter

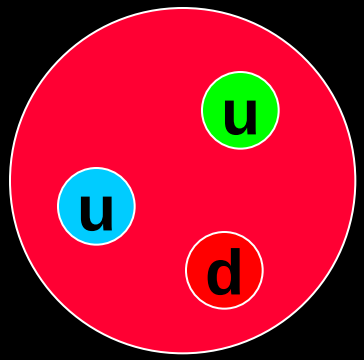
$E=mc^2$

1GeV~Proton Mass

The Matter particles

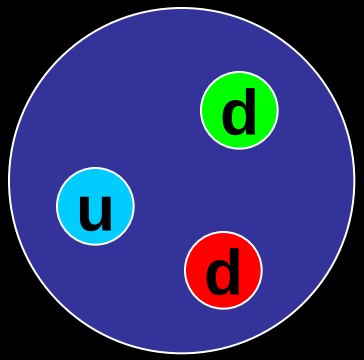


How do quarks combine?



A proton:

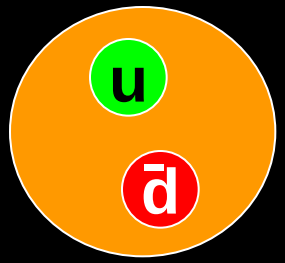
two ‘u’ quarks and one ‘d’ quark



A neutron:

2 ‘d’ quarks and 1 ‘u’ quark

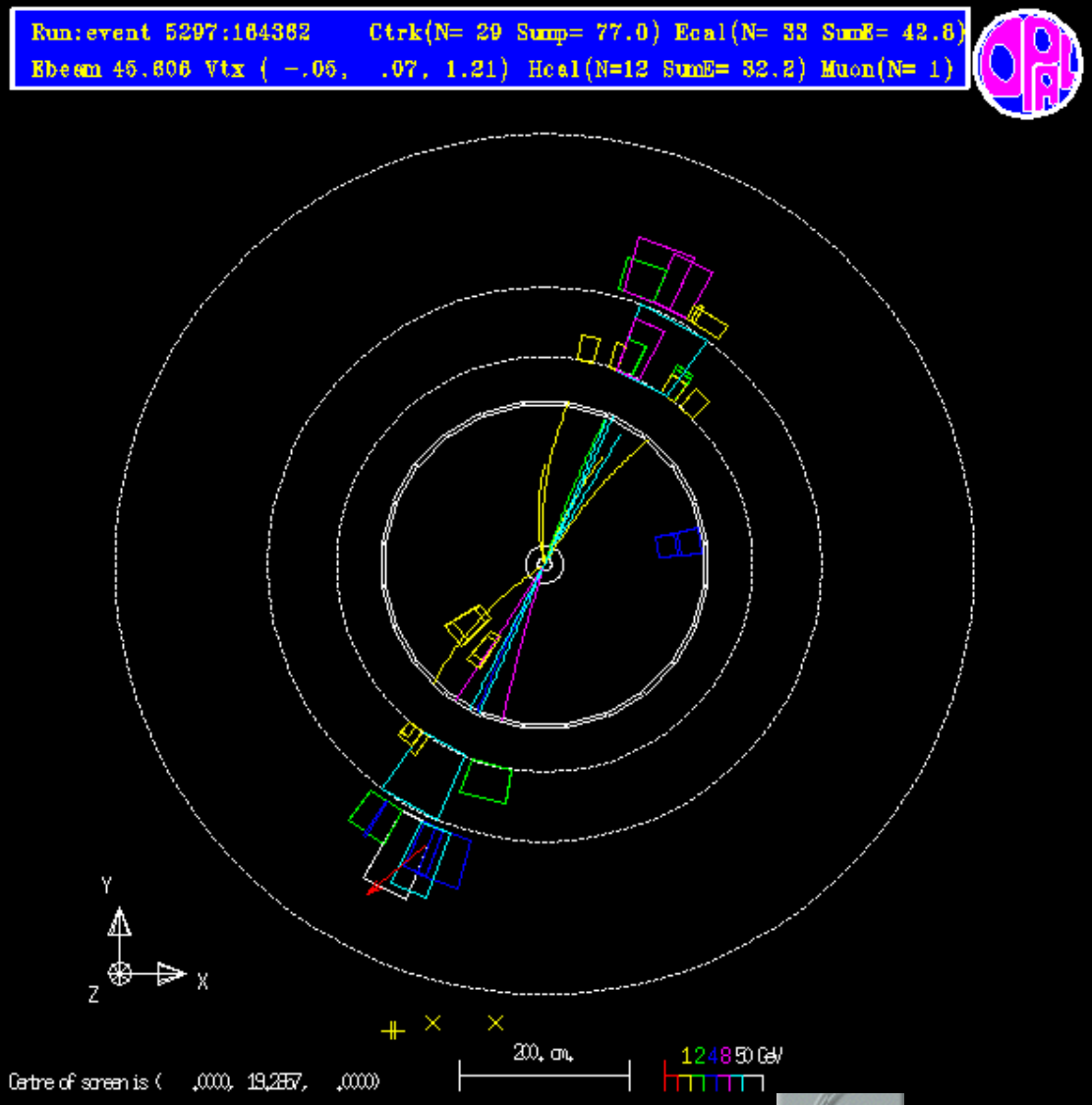
With 6 quark types there are hundreds of combinations



Mesons have a quark and an anti-quark

Many created, not stable

Can we see a quark?



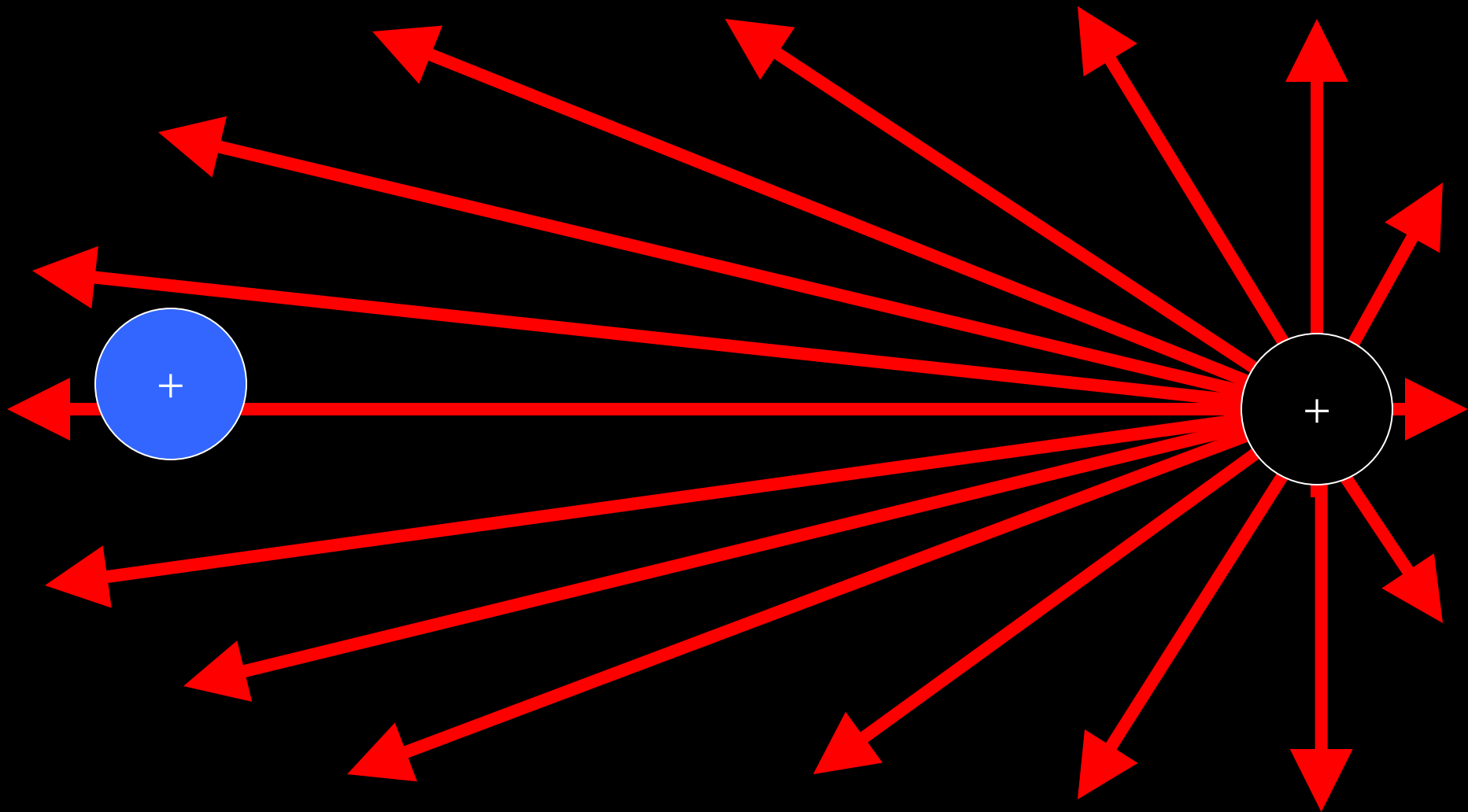
Probably not

The picture shows the result of making a pair of quarks at LEP, CERN

The quarks are not seen: A jet of ‘hadrons’ is instead

Forces in Ordinary Physics

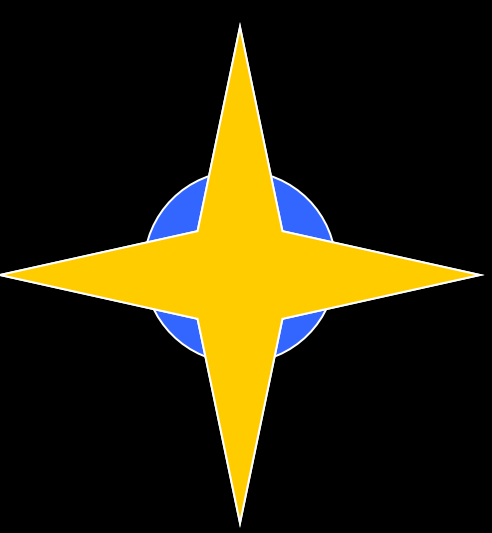
Classically, forces are described by charges and fields



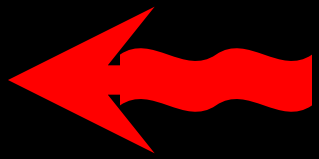
Forces in Particle Physics

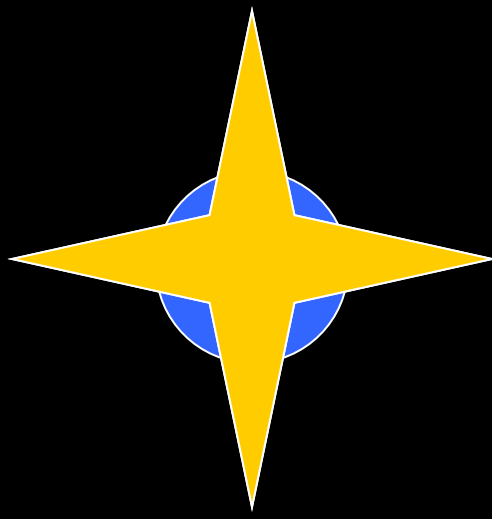
High energies and small distances ⇔ quantum mechanics

Continuous field → exchange of quanta



For Electromagnetism





The quanta are photons, γ

The Forces of Nature

Force	Realm	Particle
Electro-magnetism	Magnets, DVD players	γ
Strong	Fusion	Gluon
Weak	β-decay, (sunshine)	W^+, W^-, Z^0
Gravitation	Not in the same framework	

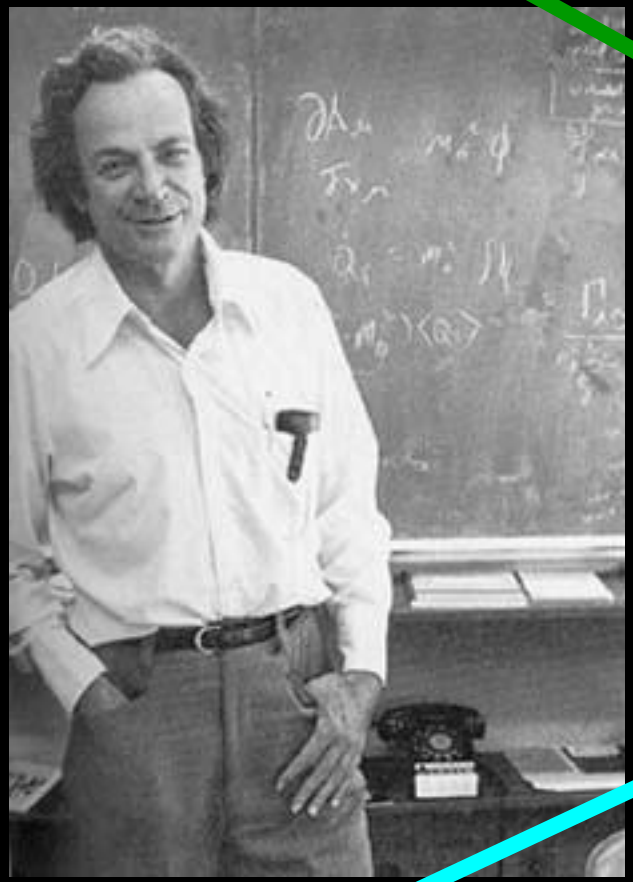
Higgs may give a link?

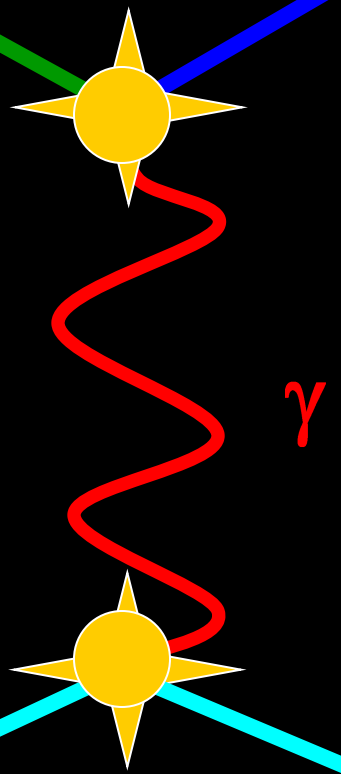
The Forces of Nature

Force	Mass, GeV	Particle
Electro-magnetism	0	γ
Strong	0	Gluon
Weak	80, 91	W's Z
Gravitation	Not in the same framework	

Mediation of the Forces

Electron





At each ‘vertex’ charge is conserved. Heisenberg Uncertainty allows energy borrowing.

Positron (anti-electron)

Feynman Diagram

Particles and forces

	‘u’ quarks	‘d’ quarks	electron	neutrino
E.M. charge	+2/3	–1/3	–1	0
Strong force	yes	yes	no	no
Weak force	yes	yes	yes	yes

Heavier generations have identical pattern

What is the Higgs boson?

- The equations describing the forces and matter particles work well.
- Unfortunately they demand that they all weigh nothing
  - We know this is not true
- Prof. Higgs proposed an addition which corrects this.

The Standard Model

The Waldegrave Higgs challenge

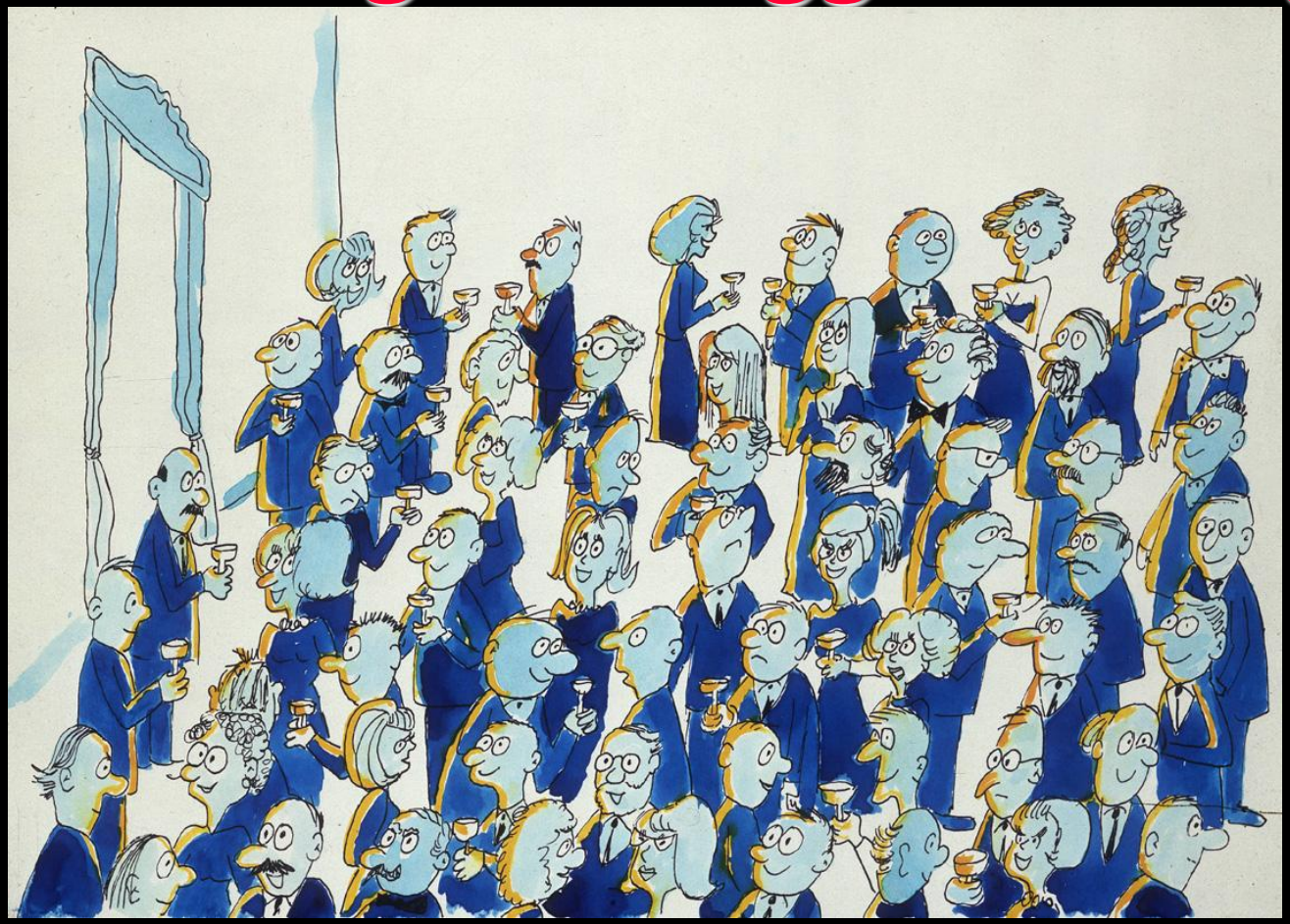
In 1993, the then UK Science Minister, William Waldegrave, issued a challenge to physicists to answer the questions:

'What is the Higgs boson, and why do we want to find it?'

on one side of a sheet of paper.

David Miller of UCL won a bottle of champagne for the following:

The Waldegrave Higgs challenge

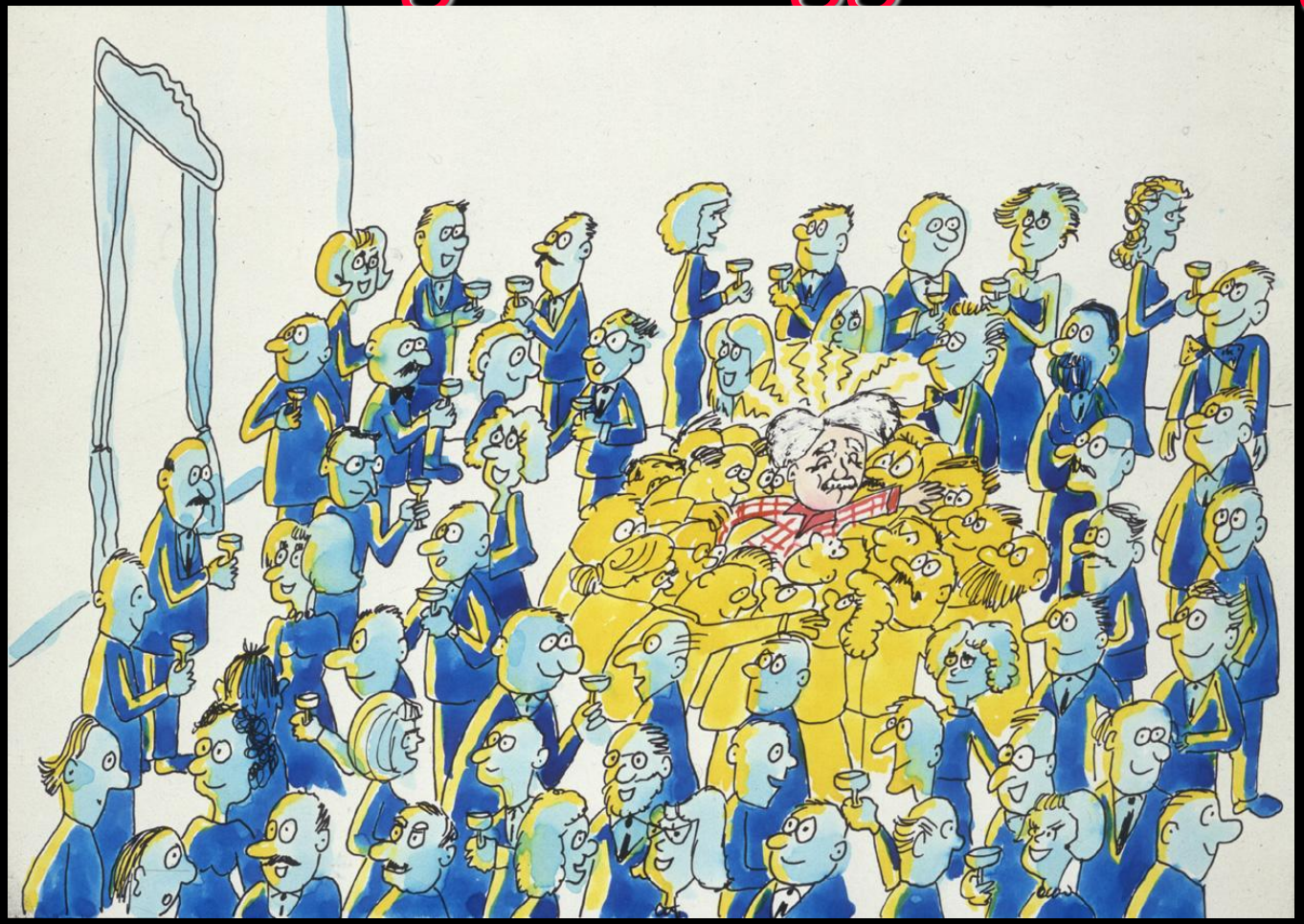


Imagine a room full of political activists

The Waldegrave Higgs challenge

The Prime Minister walks in

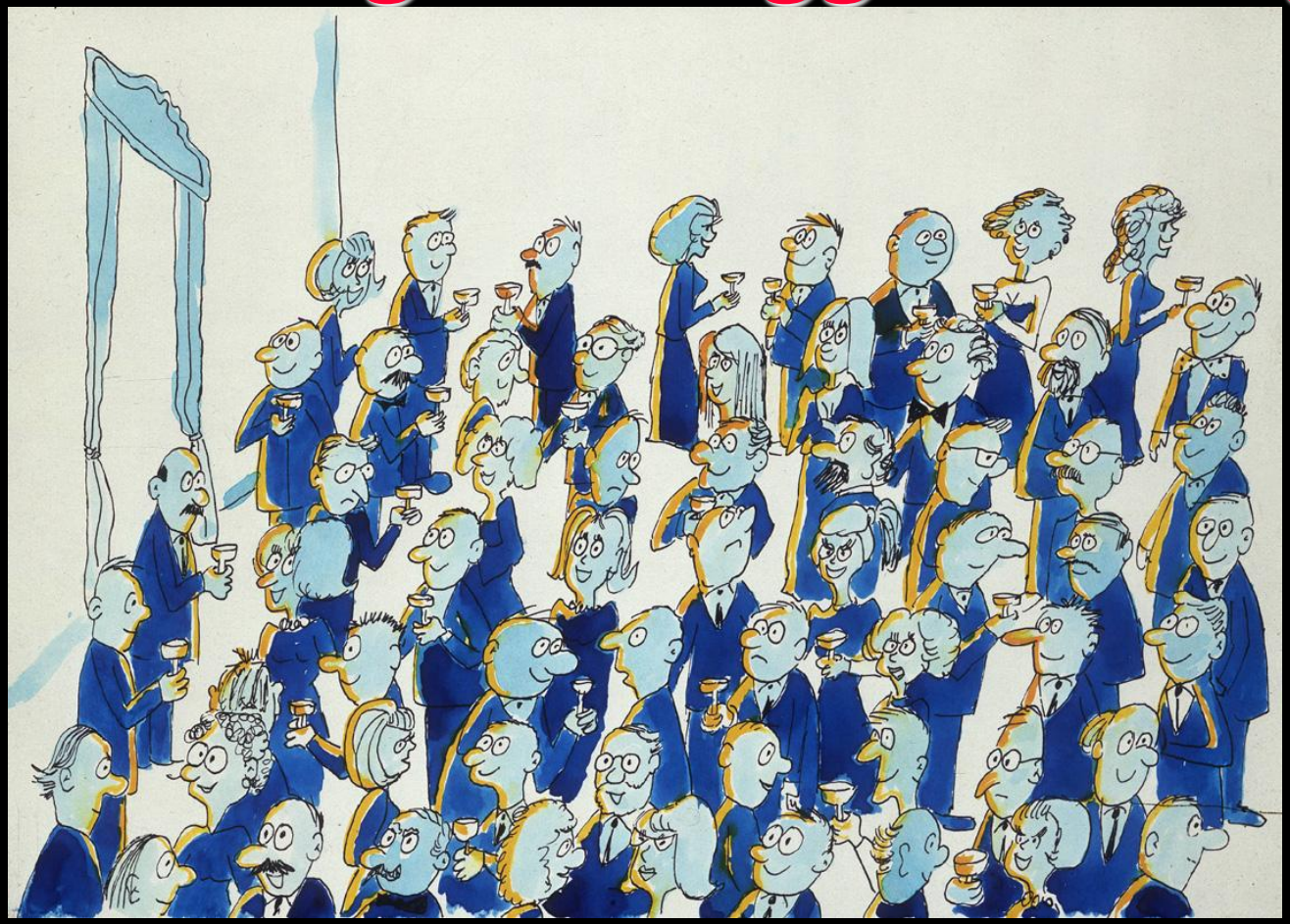
The Waldegrave Higgs challenge



He is surrounded by a cluster of people

Analogous to generation of Mass

The Waldegrave Higgs challenge



Imagine the same room again

The Waldegrave Higgs challenge

A interesting rumour is introduced

The Waldegrave Higgs challenge

Thanks to D. Miller and CERN

© Photo CERN

Soon we have a cluster of people discussing it

Analogous to Higgs boson

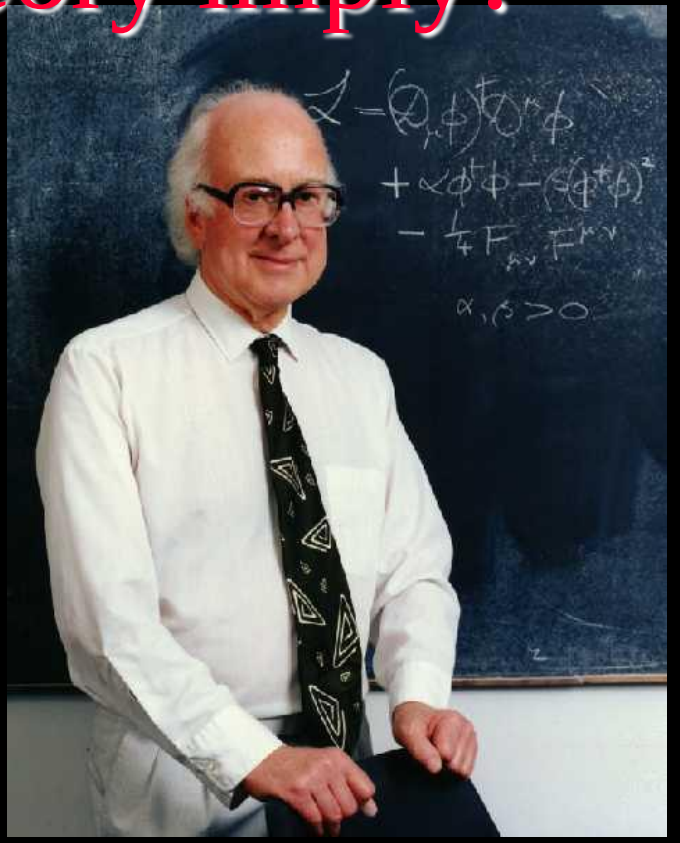
What does Higgs theory imply?

Higgs' mechanism gives mass to W and Z bosons, and to the matter particles.

Mass of the W predicted

We can check it

It also predicts one extra particle:
The Higgs boson

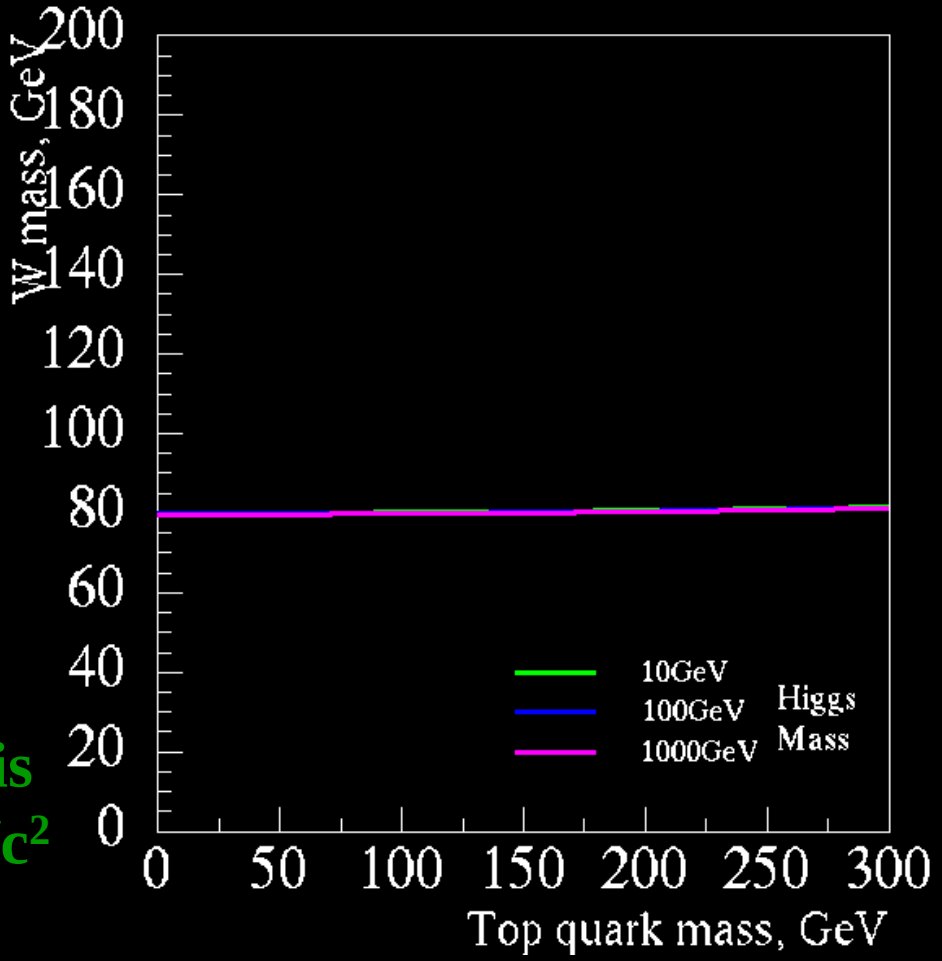


The Higgs Boson mass is *not* predicted

The W, the top quark and Higgs

- We can calculate the **mass** of the **W boson**
- Need the mass of the Z and the strength of the forces; **these are well known**
- It is also affected by:
  - **Top quark** mass: **Weak effect**
  - **Higgs** mass: **Tiny effect**

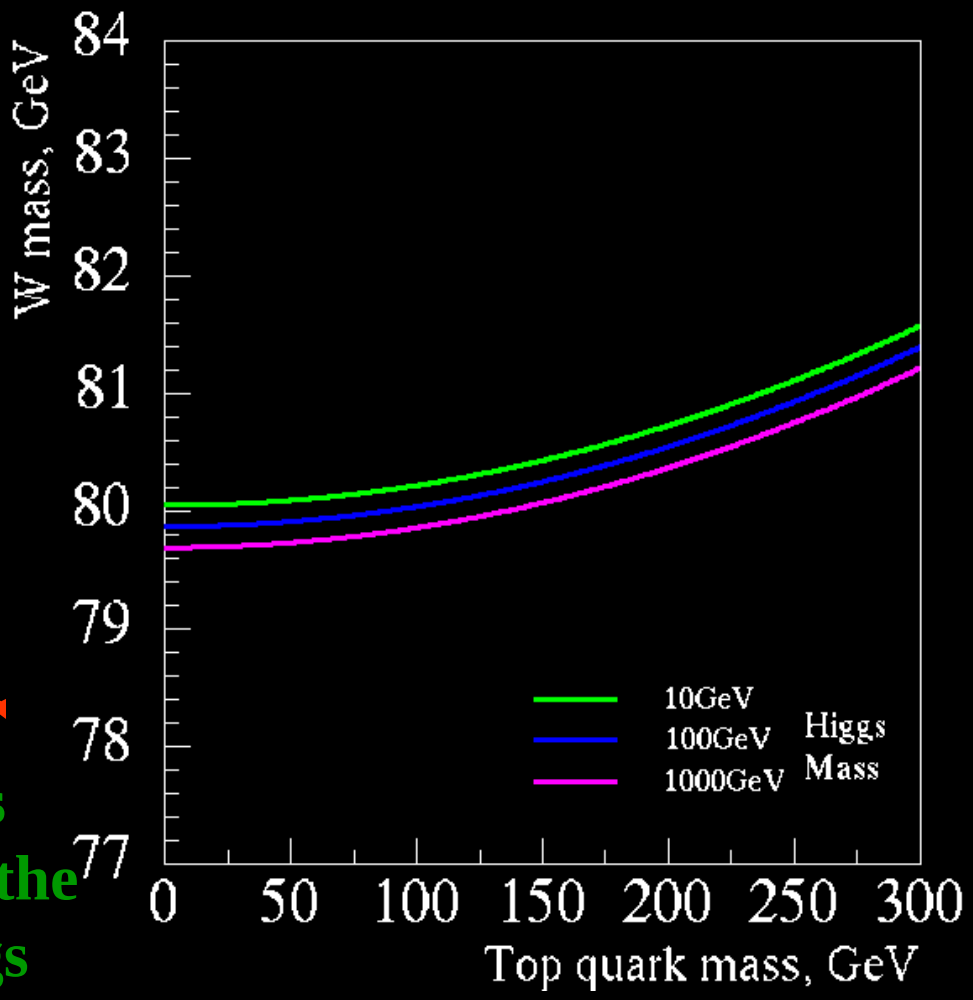
The W, the top quark and Higgs



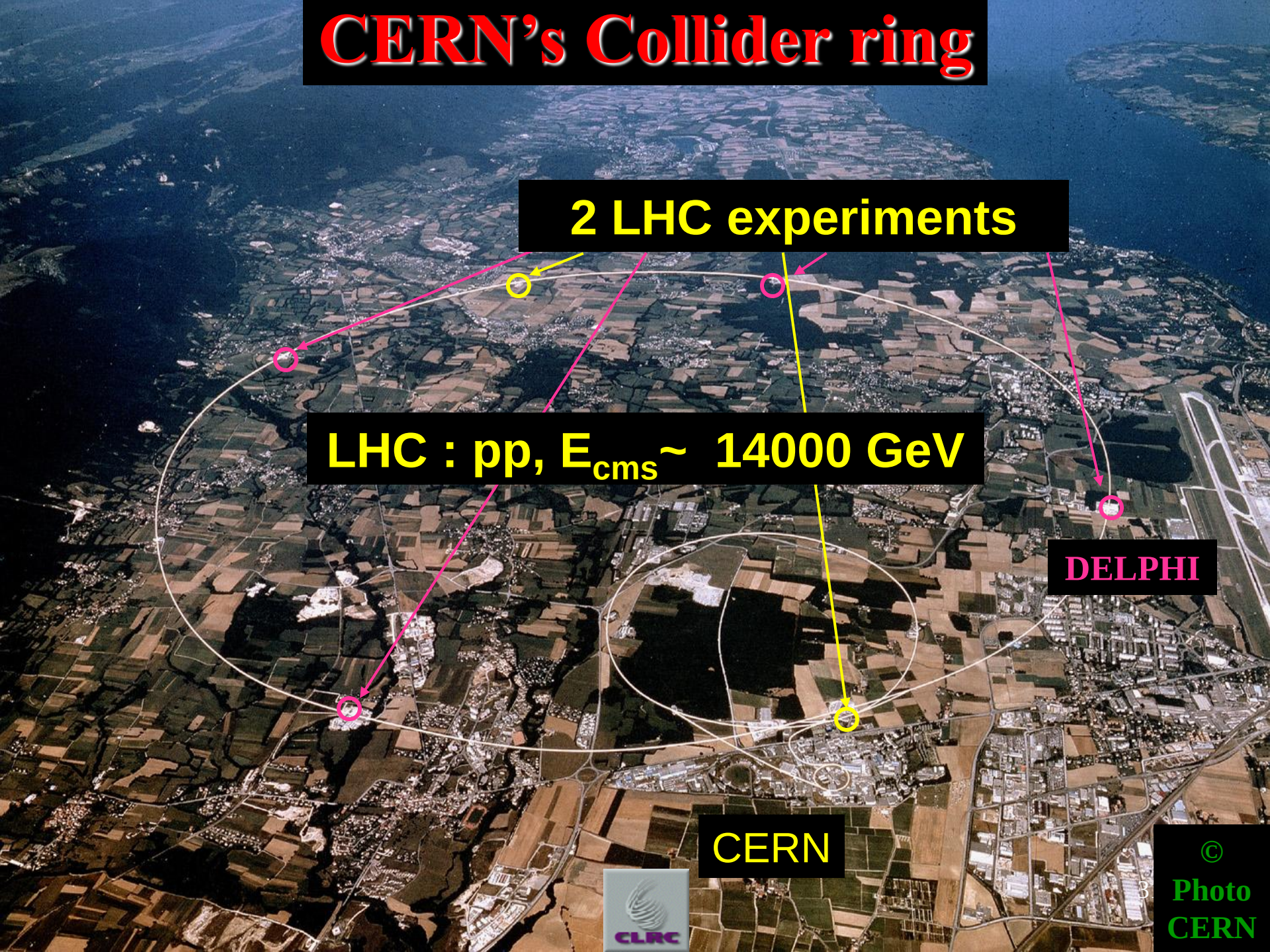
The W mass is about 80GeV/c^2

The W, the top quark and Higgs

Expanded scale



The W mass depends upon the top and Higgs masses


CERN's Collider ring
2 LHC experiments
LHC : pp, E_{cms}~ 14000 GeV
DELPHI
CERN
CLRC
© Photo CERN

What are LEP and LHC?

	LEP	LHC
Beams of	Electrons	Protons
Energy, GeV	208	14,000
Max. Higgs Mass	115	~1000
Detailed?	Yes	No
Operation	1989-2000	2006-

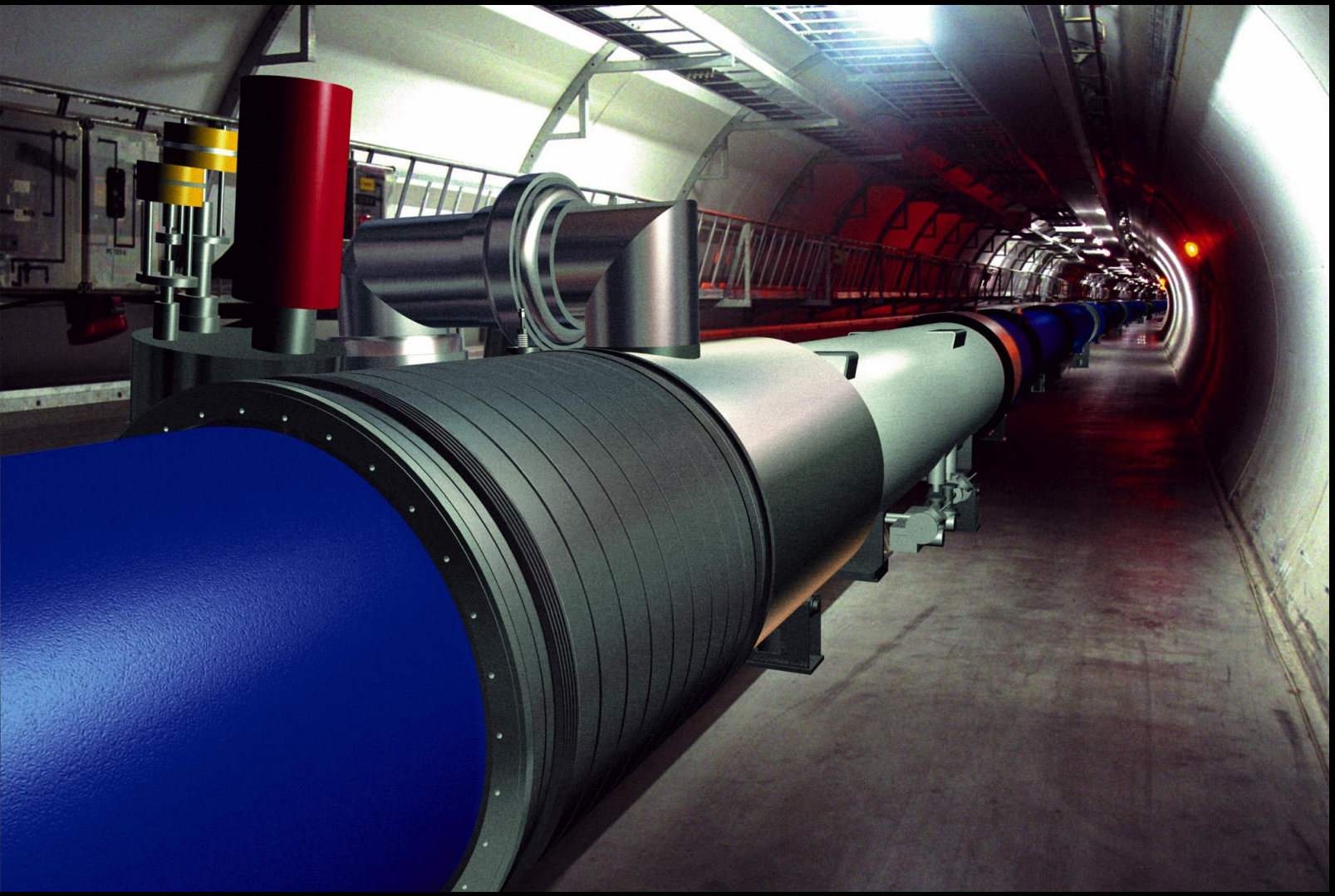
Work started 1980's

Complementary machines – but needing the same tunnel

In the LEP tunnel

27km of vacuum pipe and bending magnets

Now to be the LHC tunnel



27km of vacuum pipe

8.3Tesla bending magnets,

3^{o} above absolute zero

© Photo CERN

One experiment: 'OPAL'

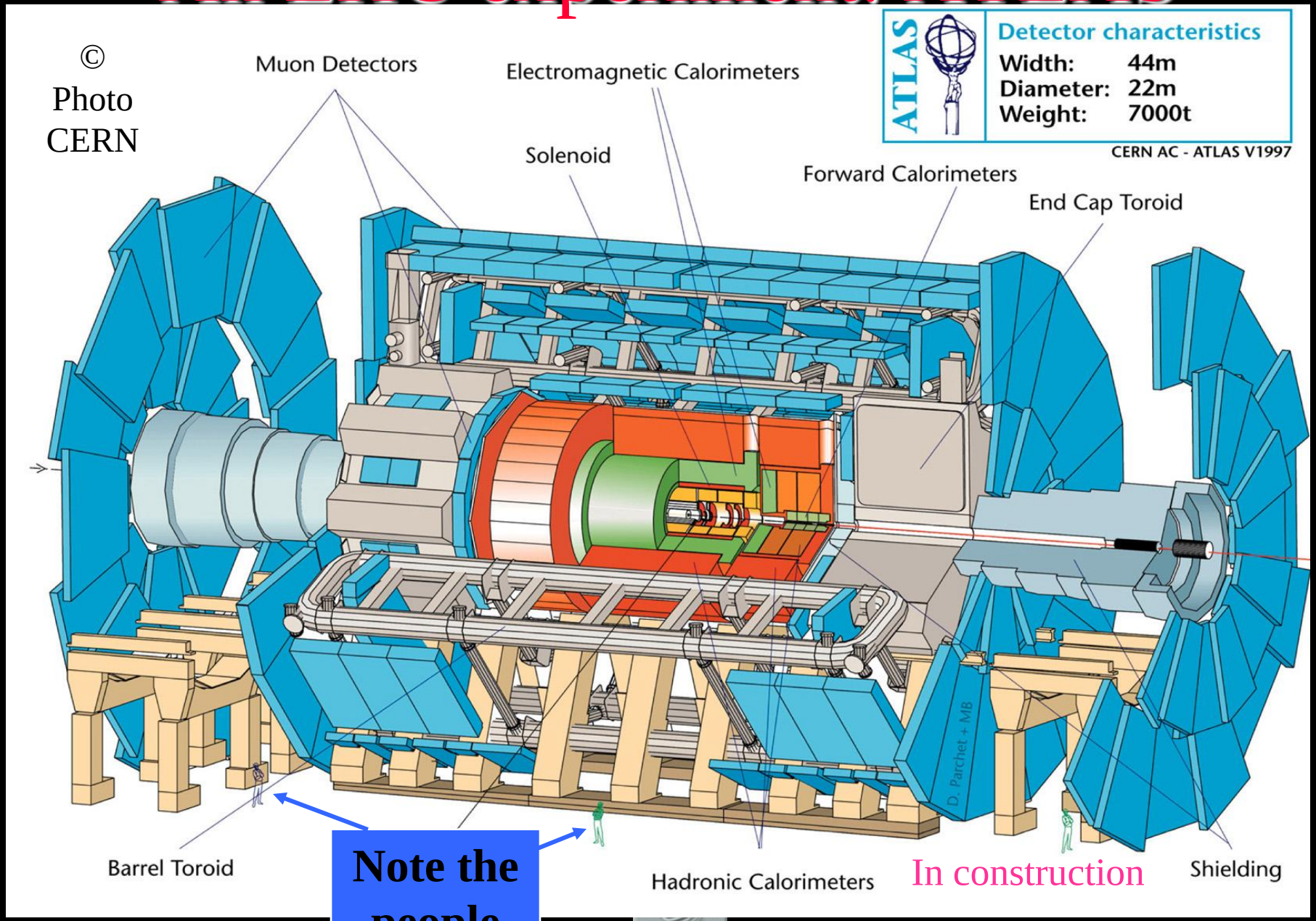
One of four rather similar detectors

© Photo CERN

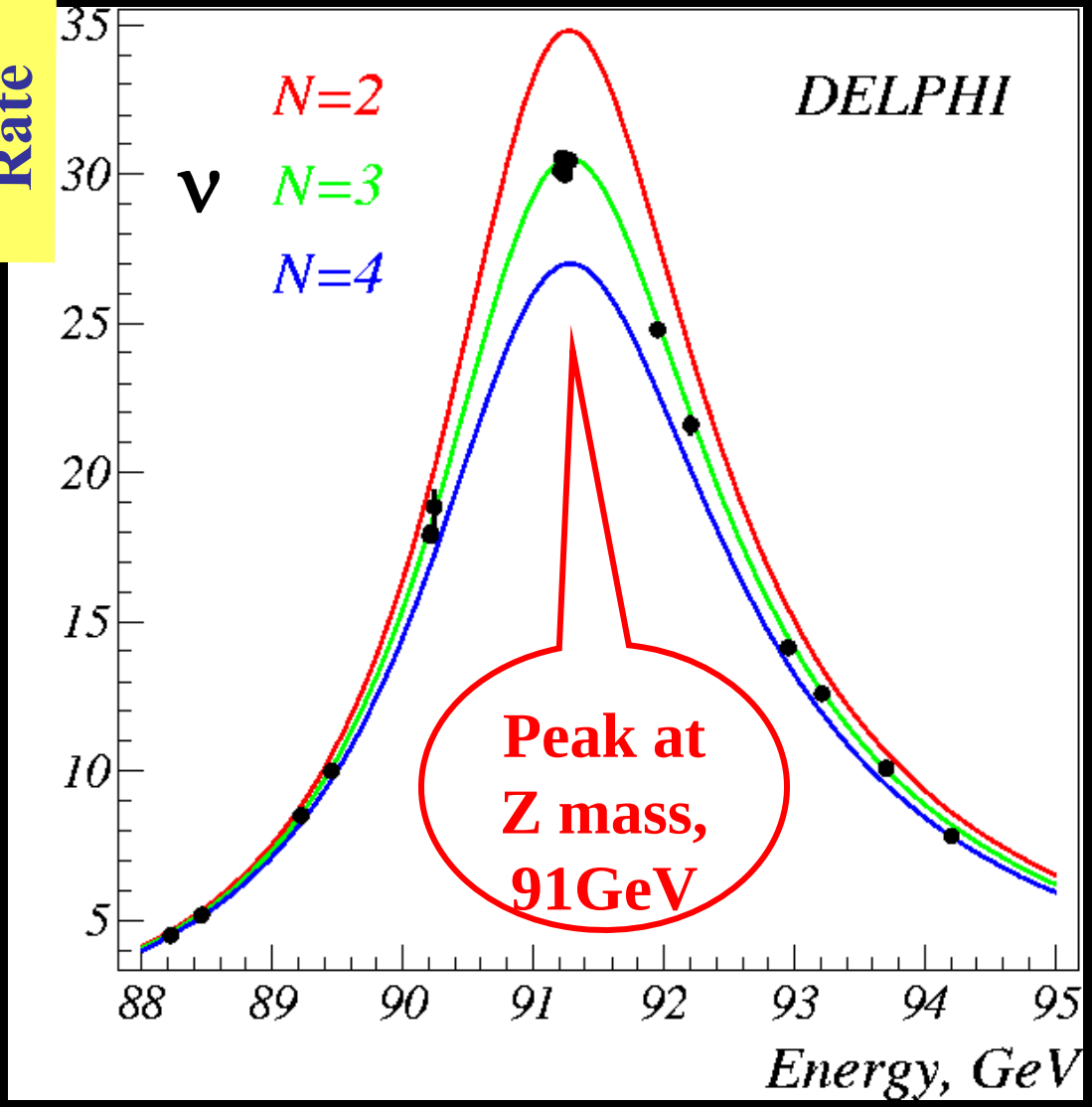
Assembly in 1989

Note the people

An LHC experiment: ATLAS



Z studies at LEP



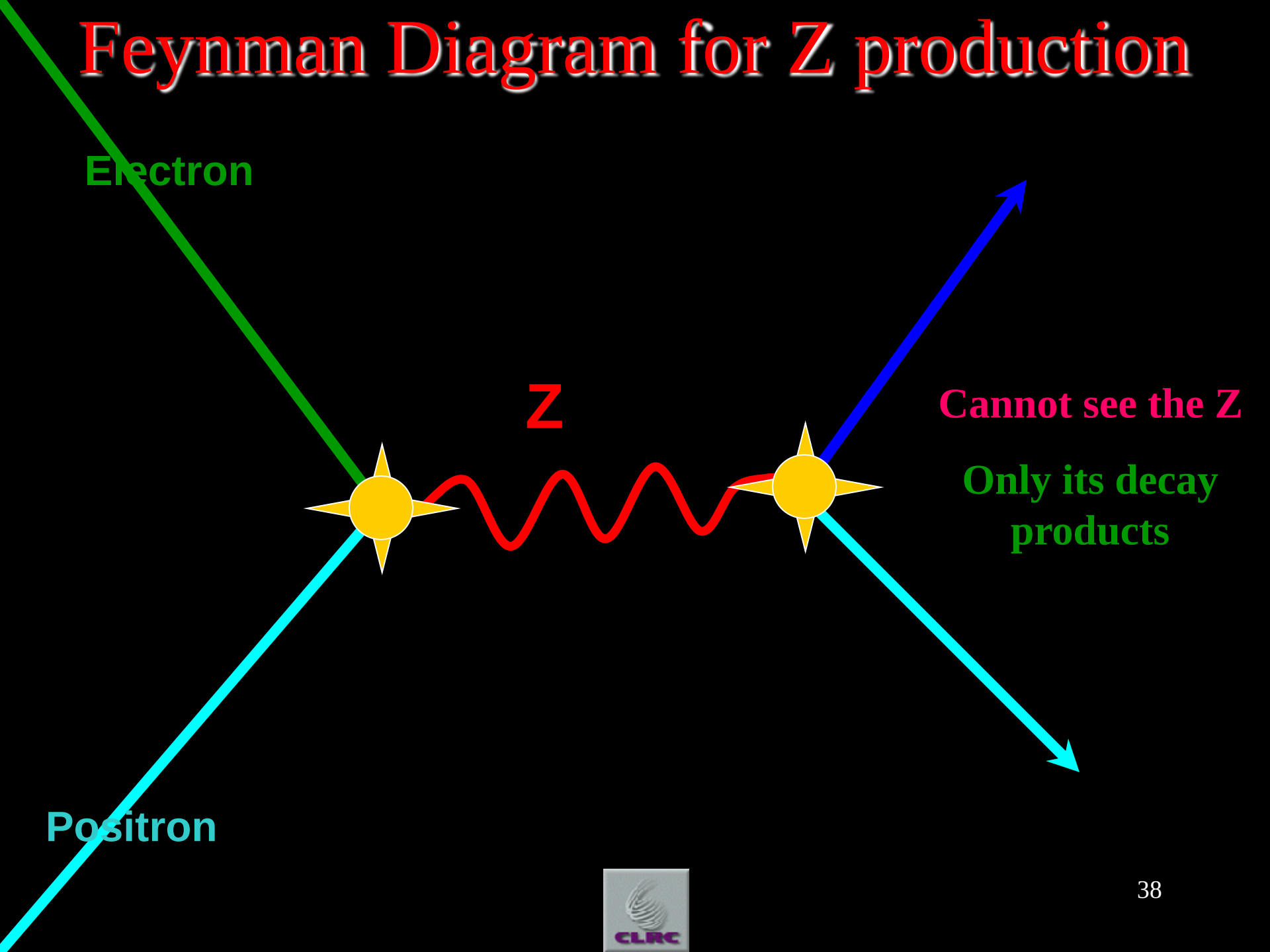
From 1989 to 1995 LEP created 20,000,000 Z bosons

These were used for detailed studies of its properties

Here you see the analysis which established the number of neutrinos as 3

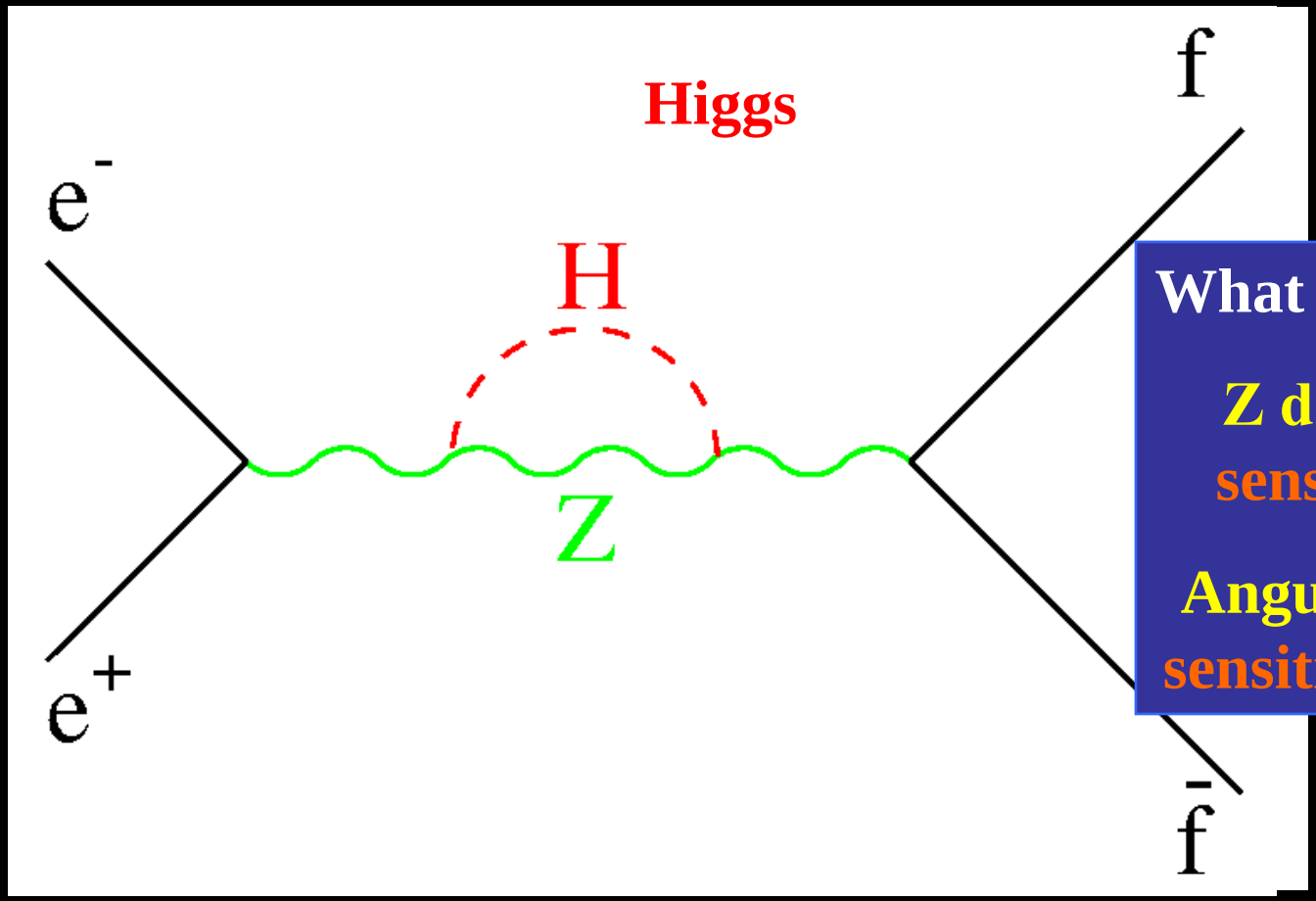
They can say something about the Higgs too.

Feynman Diagram for Z production



Indirect Search for the Higgs Boson

Properties of the Z boson changed by 'loop' effects:

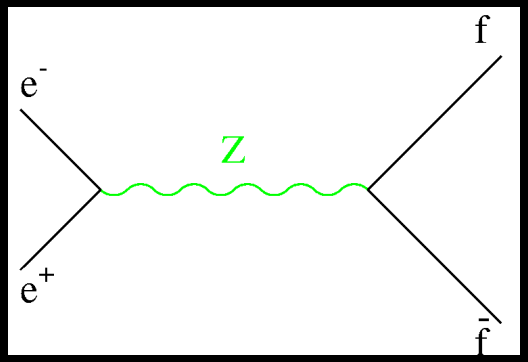


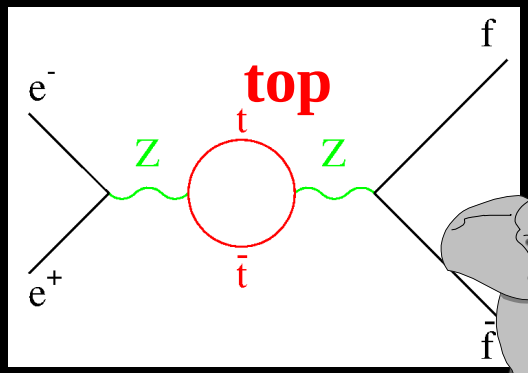
What is affected?

Z decay rate to b's - sensitive to top mass

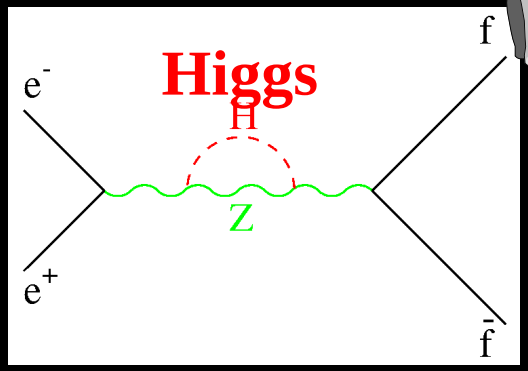
Angular distributions - sensitive to W & H mass

Indirect Search for the Higgs Boson

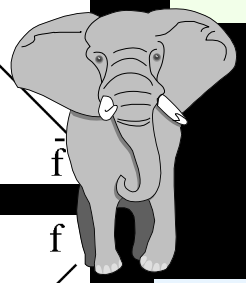


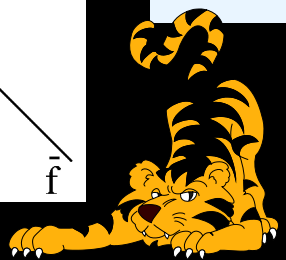


$\approx 1\%$



$< 1\%$



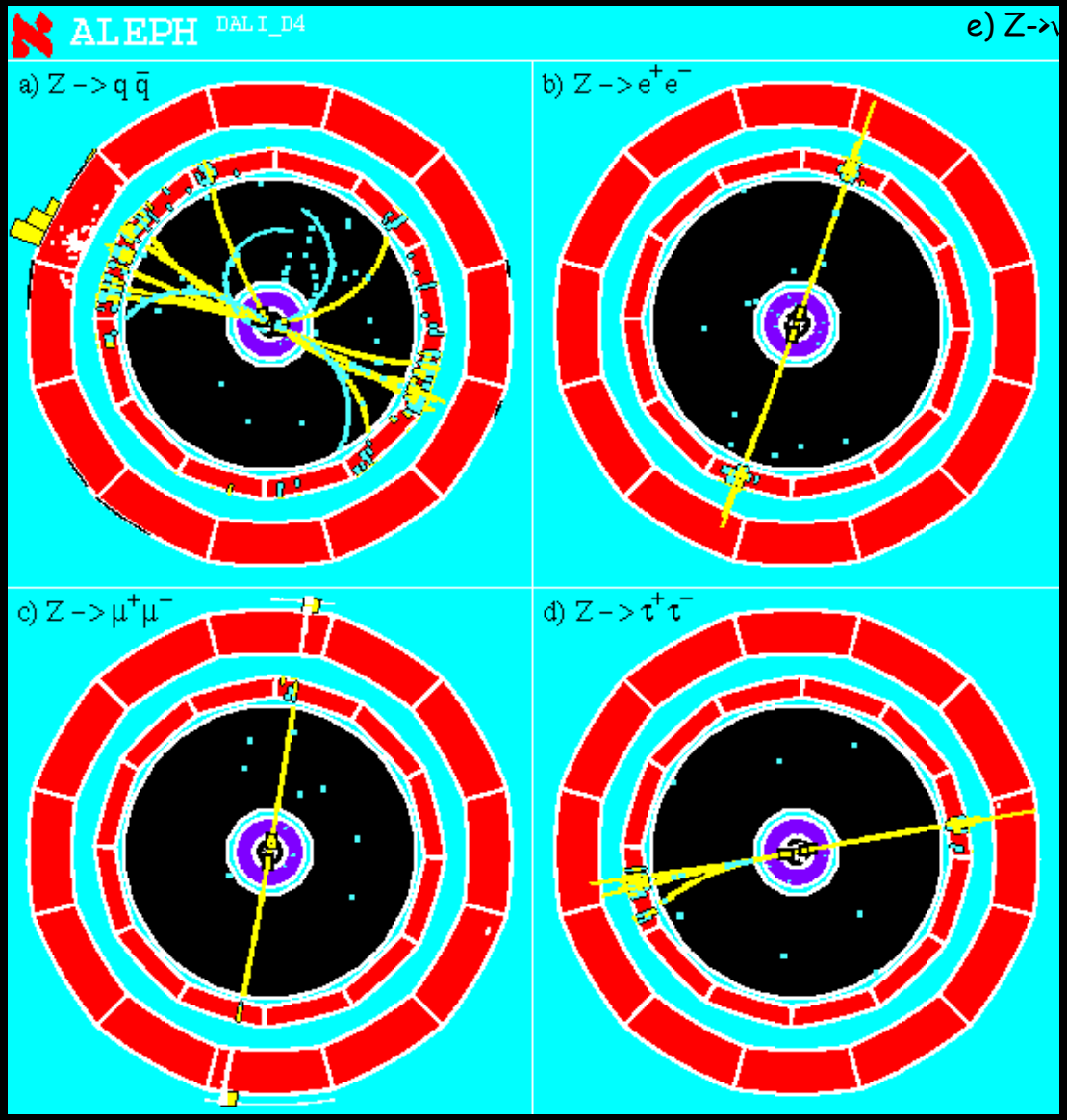


0.1% Precision needed

By carefully studying Z's we:

- **Predict m_{top} and m_W;**
  Compare with measurements;
- **Predict m_H,**
  Compare with measurements.

How to recognize Z decays:

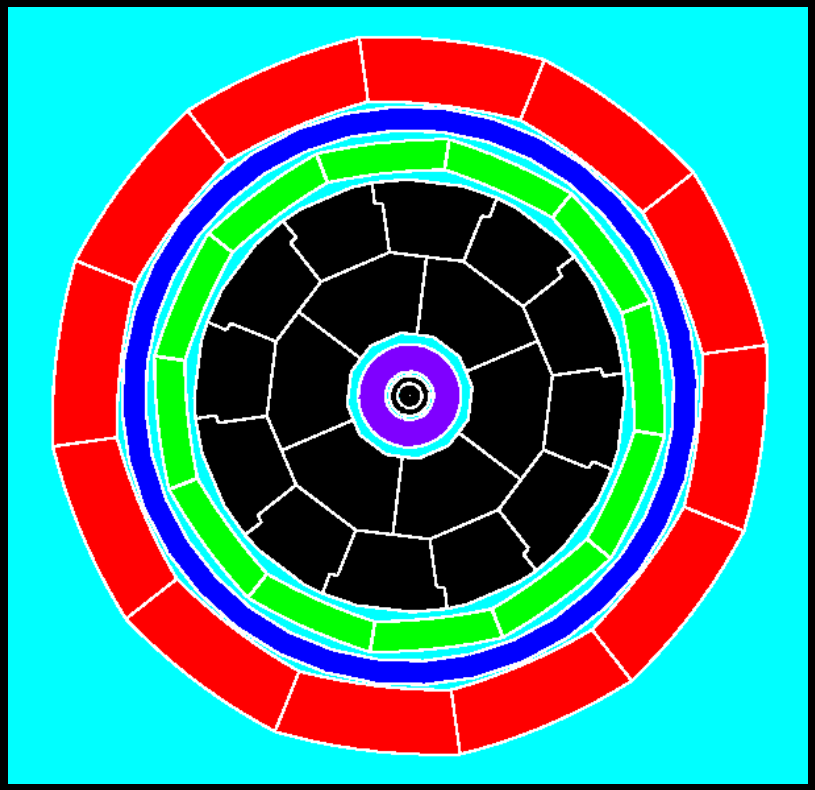


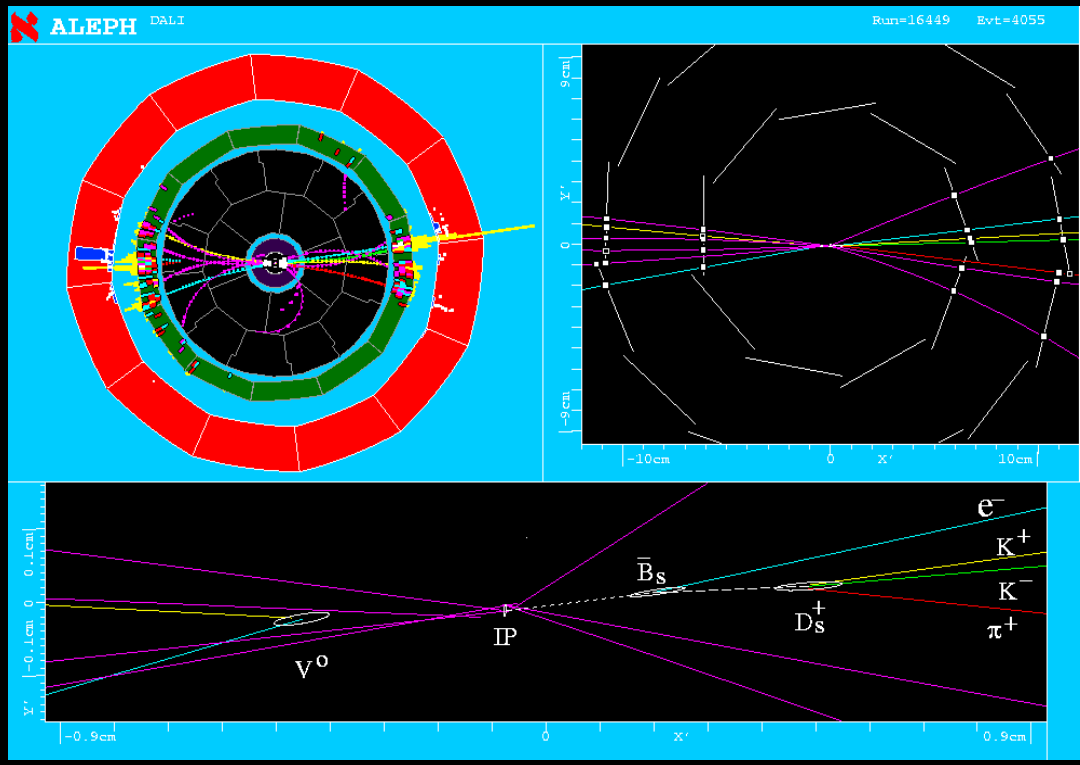
$Z \rightarrow q\bar{q}$: Two jets, many particles

$Z \rightarrow e^+e^-$, $\mu^+\mu^-$: Two charged particles (e or μ.)

$Z \rightarrow \tau^+\tau^-$: Each τ gives 1 or 3 tracks

How to recognize Z decays:





$Z \rightarrow \nu\bar{\nu}$:
Not detectable.

(weak and slow decays to lighter quarks)

$Z \rightarrow b\bar{b}$: Like $q\bar{q}$ events, with detached vertices, measured in accurate vertex detectors

One example Z distribution:

- This distribution depends on the W mass

Many things are used:

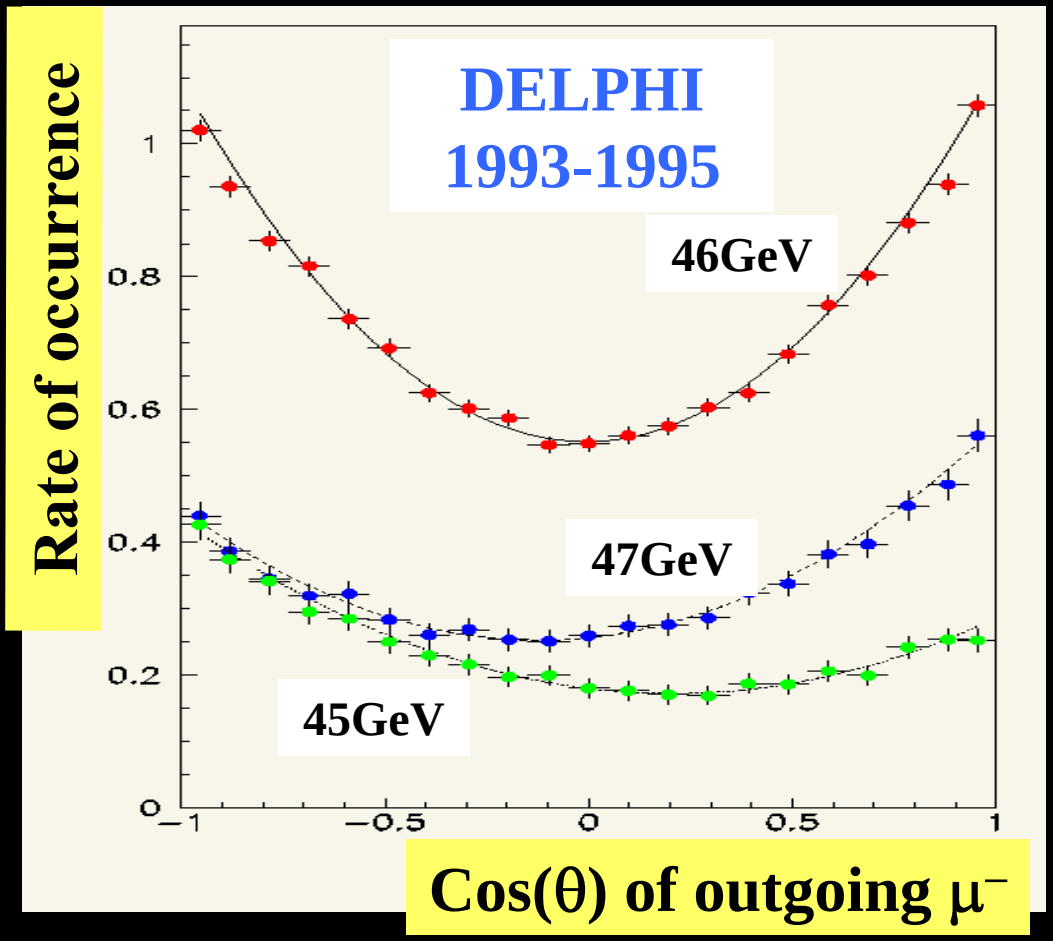
Z mass,

Several angular distributions,

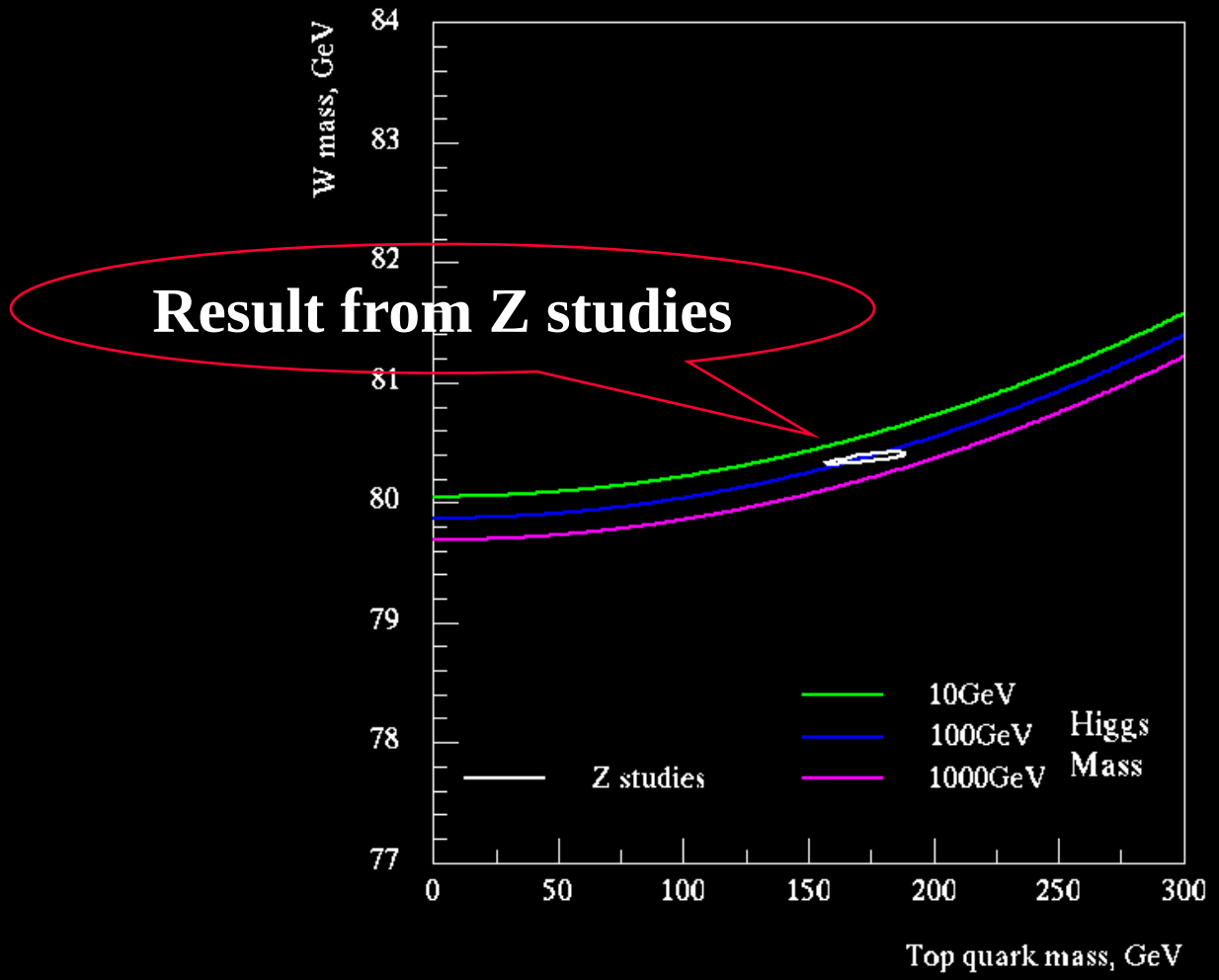
Z decay fraction to bb

Angular distributions

$Z \rightarrow \mu^+\mu^-$



The W, the top quark and Higgs



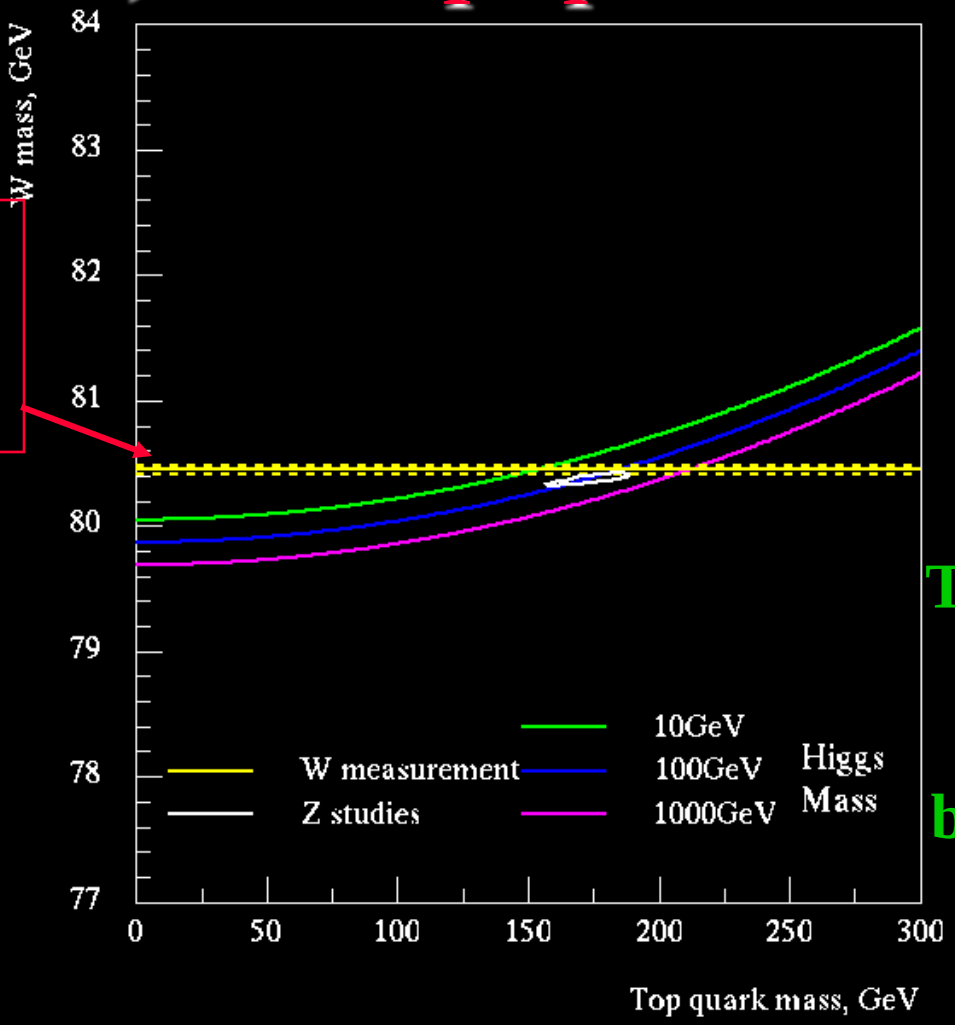
The W and top masses from Z studies agree with theory

i.e. they lie on the curves

They can be checked by direct measurement

The W, the top quark and Higgs

W mass from LEP and Tevatron

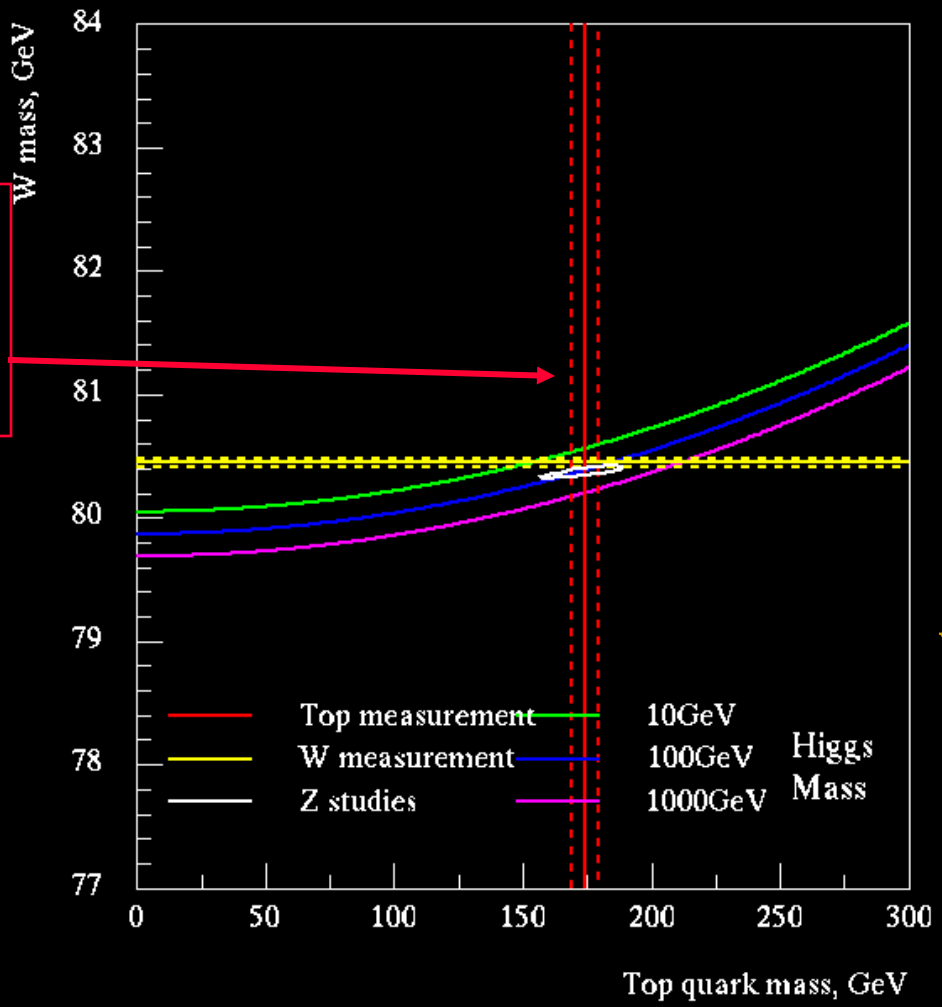


Completely consistent!

This suggested the top quark had a mass of 175GeV before it had been discovered

The W, the top quark and Higgs

Top mass from Tevatron

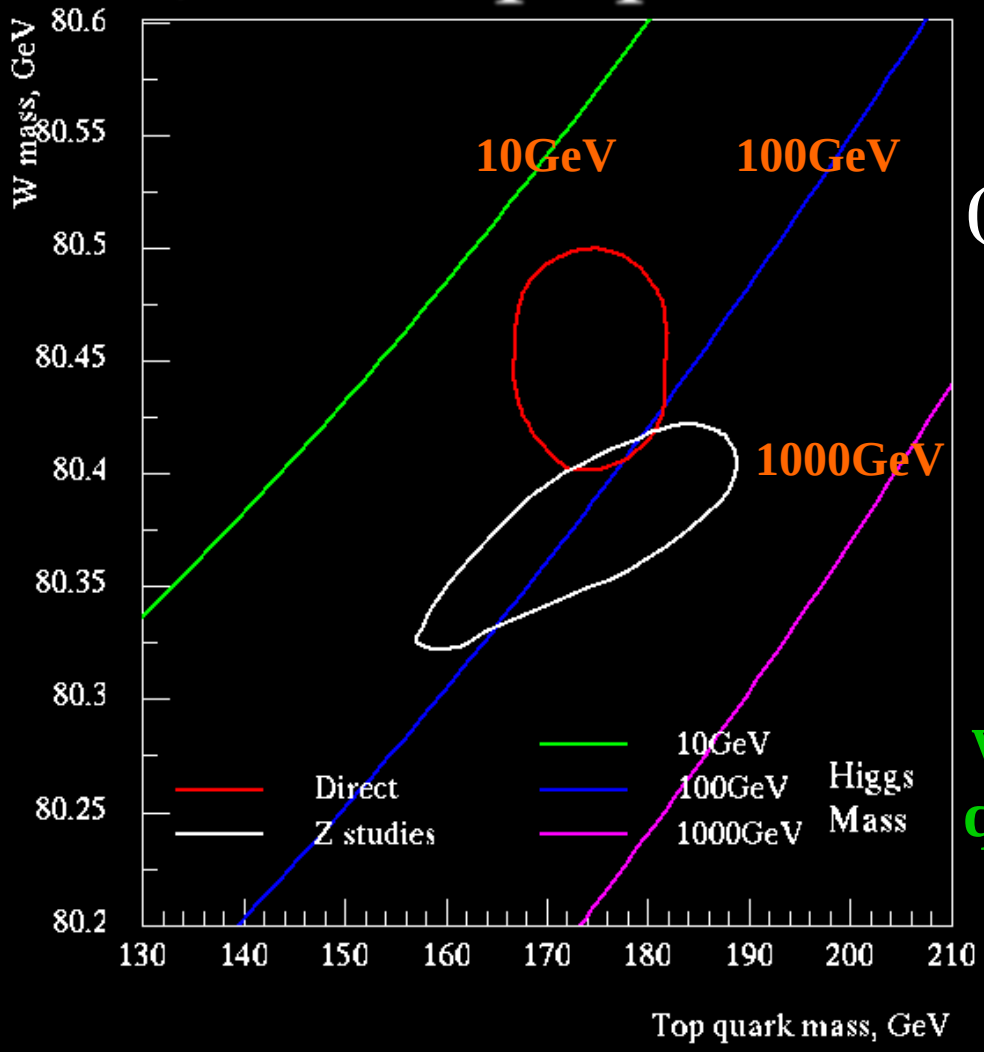


Again, incredible consistency

The top mass directly measured agrees completely with the predicted one

The W, the top quark and Higgs

Scale has been expanded further



The data (especially if they are averaged) suggest a Higgs mass around 100GeV

This procedure worked for the top quark. Will it work again?

Summary of model

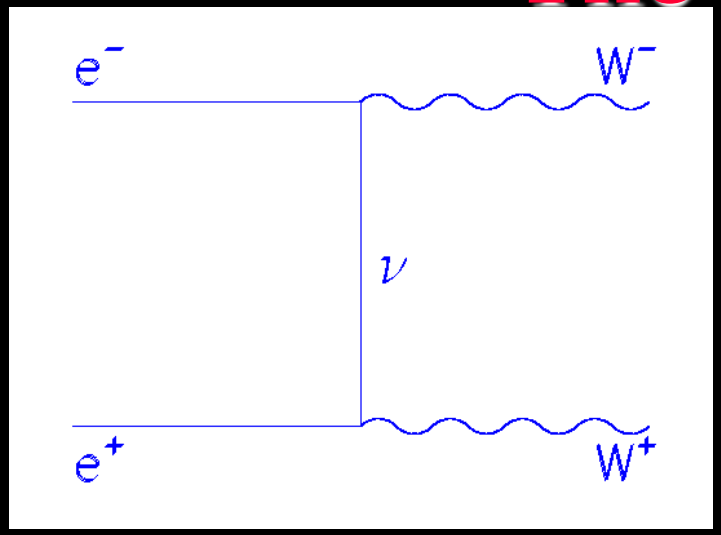
- W mass agrees with Higgs theory
  - to 1 part in 1000
- Electro-weak corrections verified:
  - W mass agrees with prediction
  - Top mass agrees with prediction
- Higgs mass should be:

$$85^{+54}_{-34}\,GeV$$

The Search for the Higgs

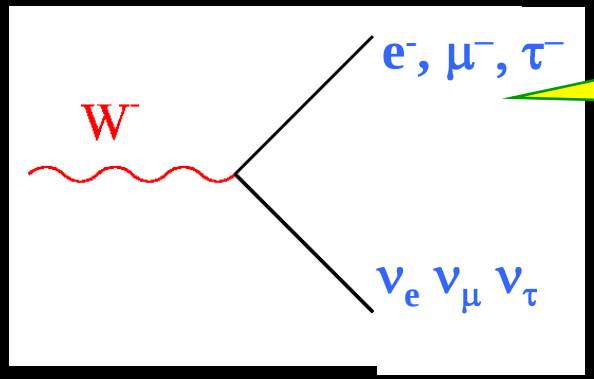
- In the late 1990's 'LEP' at CERN ran with enough energy to make W pairs
- There was also hopes it might make a Higgs.

The W pairs:



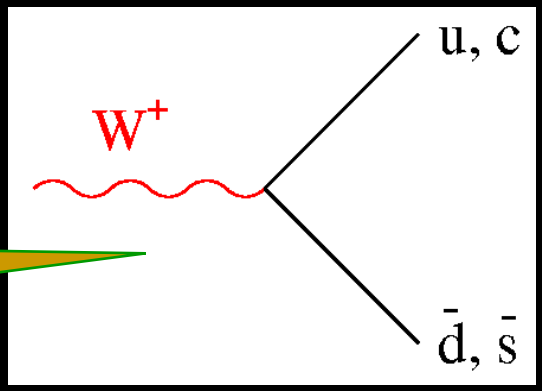
W's produced by reactions like this one

Each W decays in ~10^{-26} seconds



Into leptons (3 sorts)

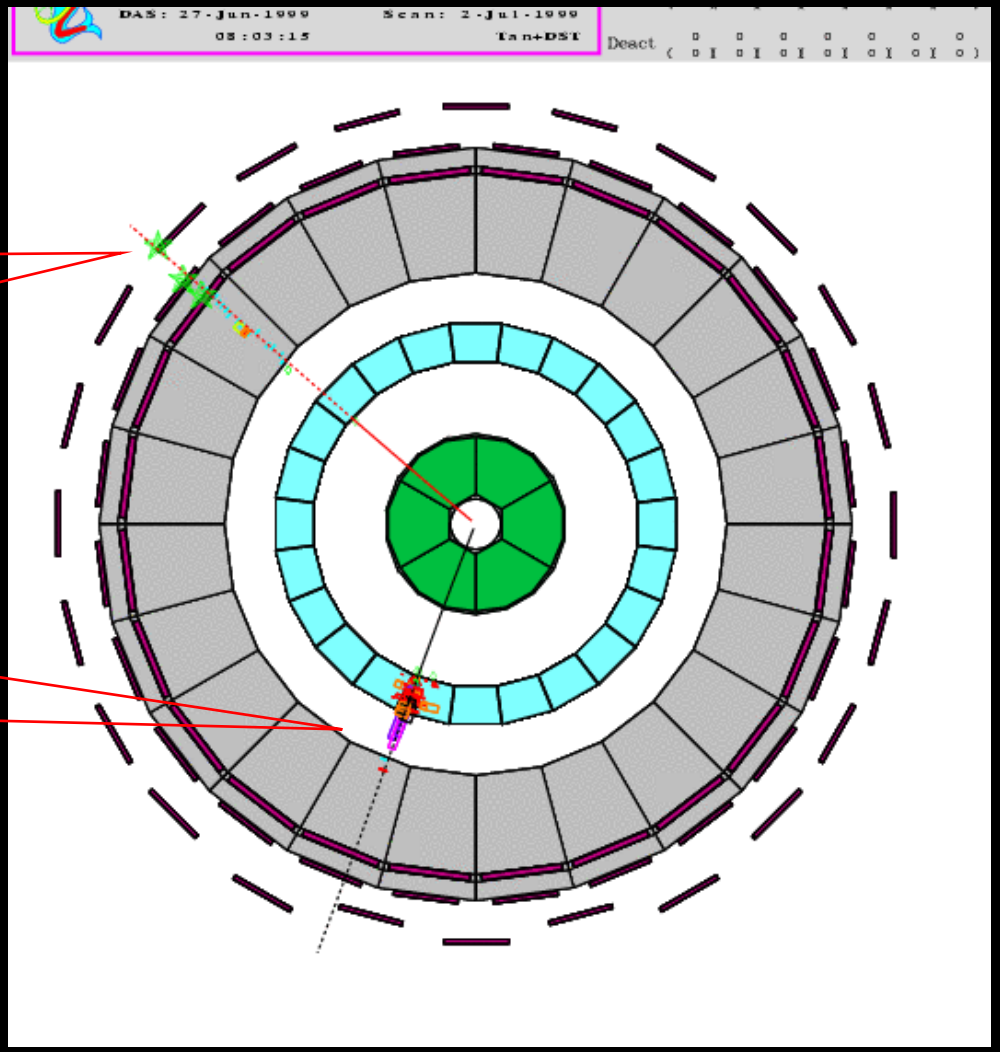
Or quarks (2 sorts)



W^+W^-: What do we see?

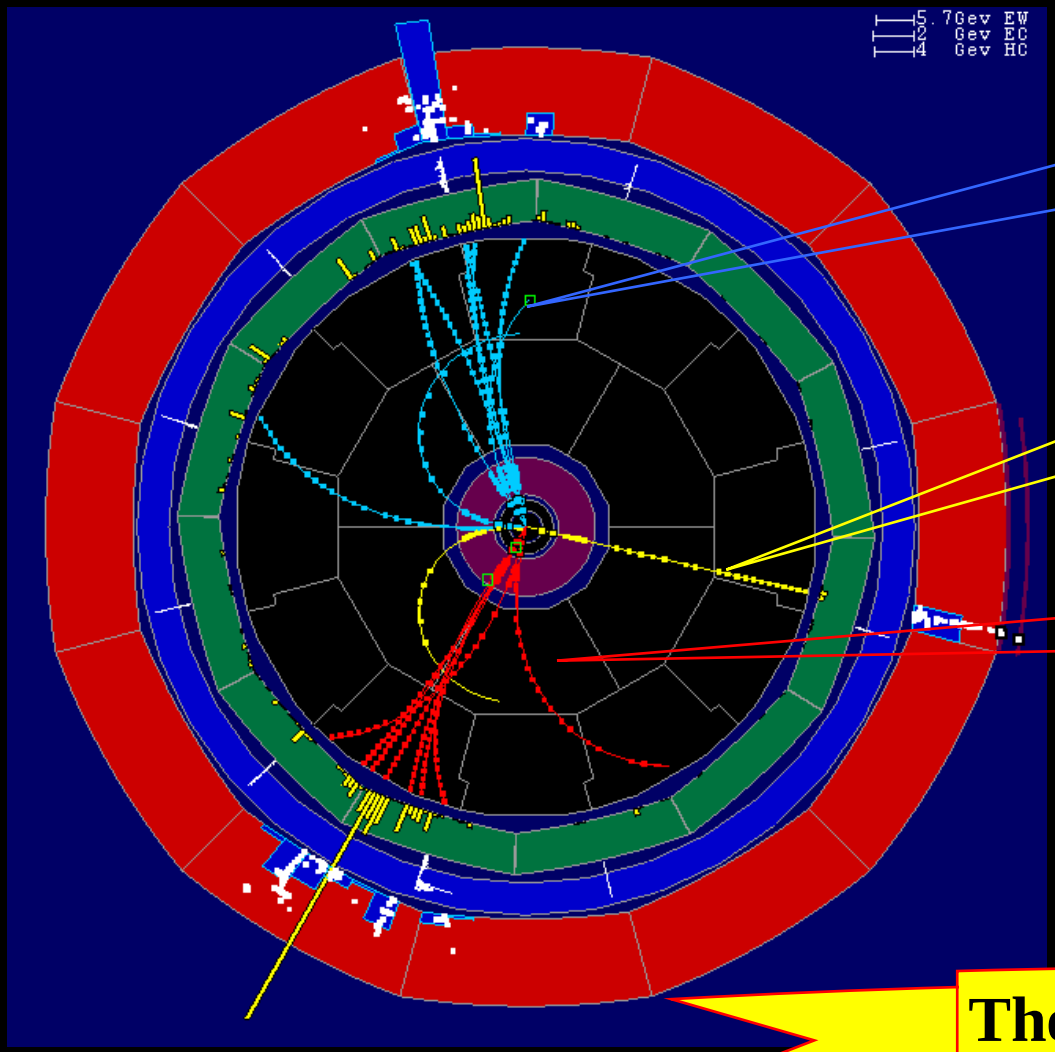
A muon

An electron



Both W's decayed to leptons

W^+W^-: What do we see?



A jet from a quark

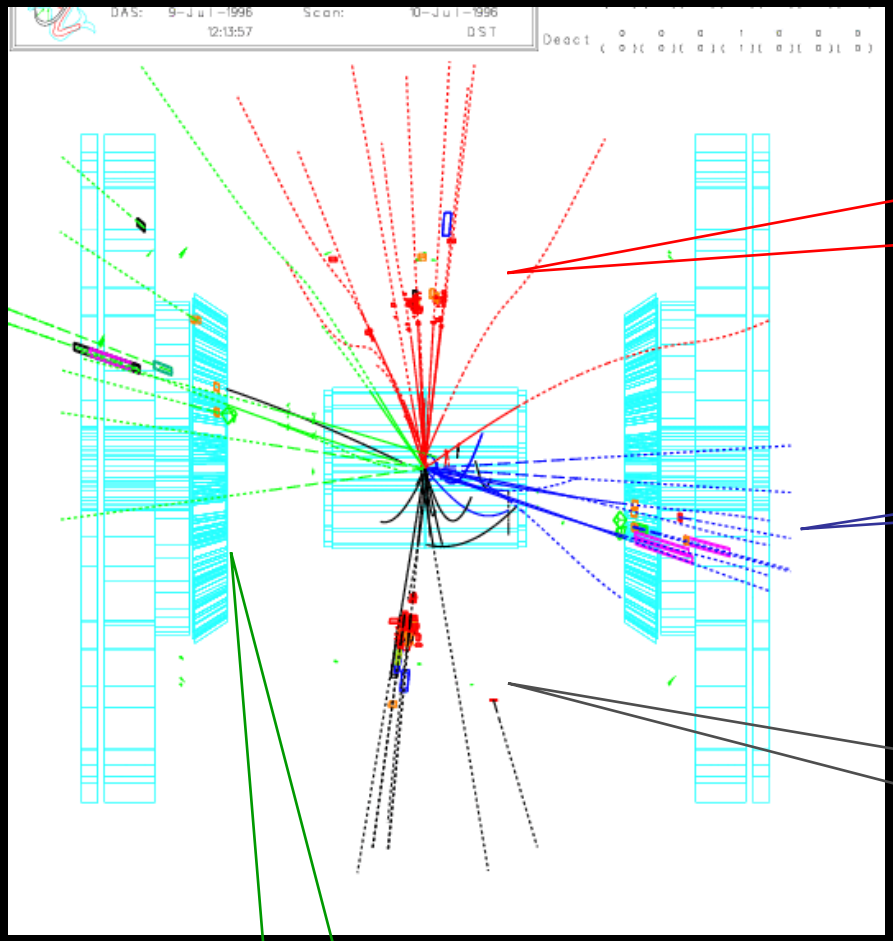
A muon

A quark

One W as 2 quarks, the other as leptons.

The nicest signature

W^+W^-: What do we see?



A jet from a quark

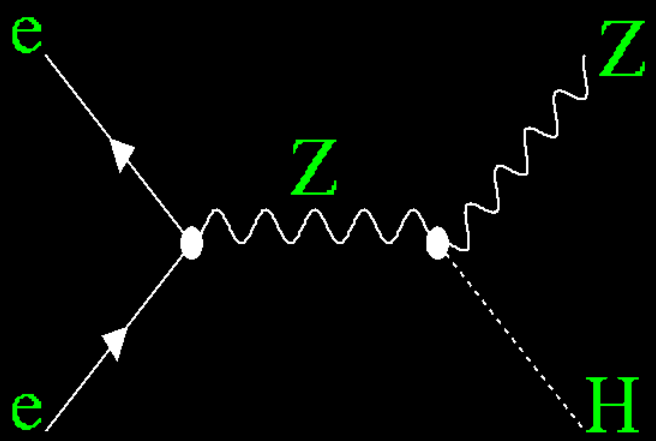
A quark

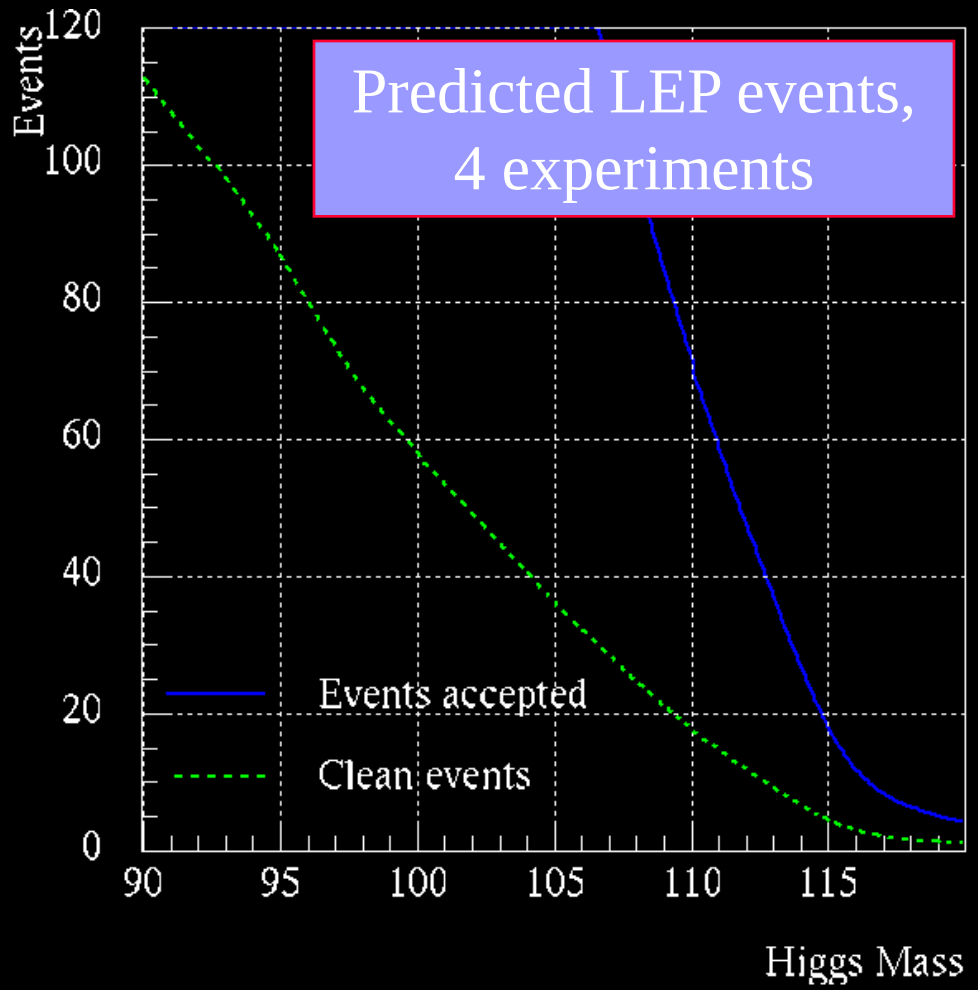
A quark

A quark

Both W's decayed to 2 quarks

How could LEP make a Higgs ?





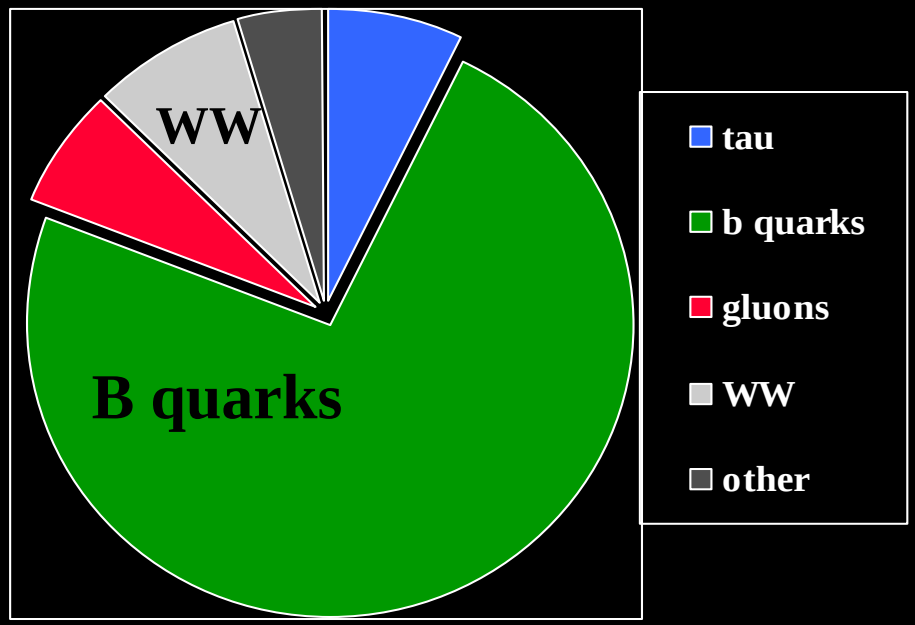
Make a Higgs and a Z together

So need Energy greater than Higgs mass plus Z mass

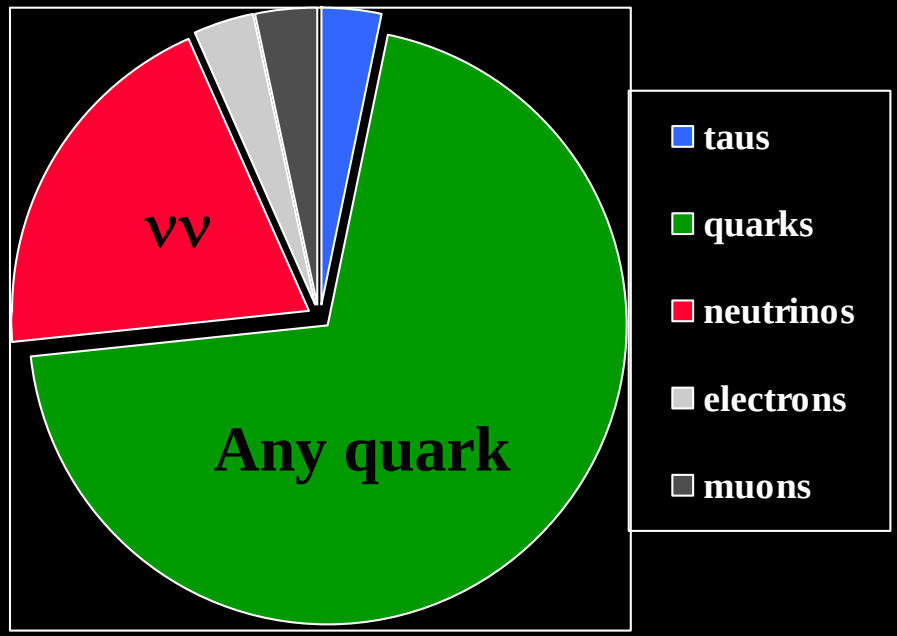
Higgs and Z decay channels

Recall: Both Z & H are made

Higgs decay modes



Z decay modes

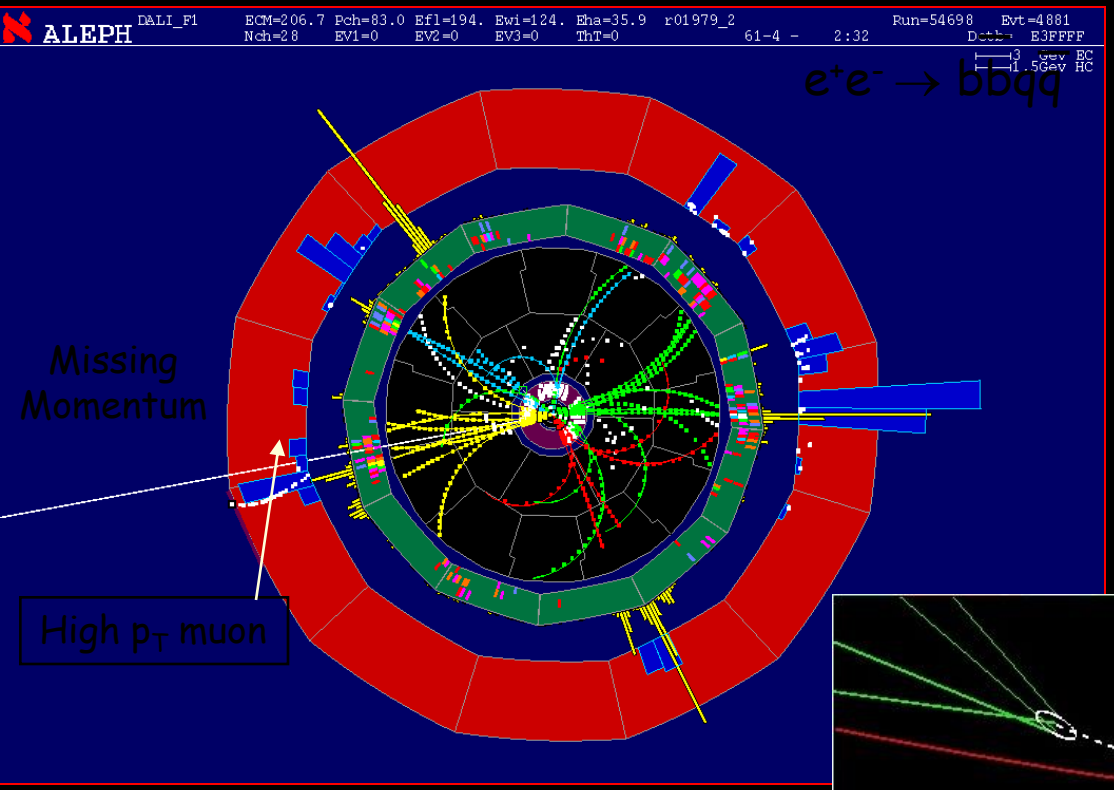


e.g. ZH→ννbb

All Z decay modes used

Higgs only into b-quarks

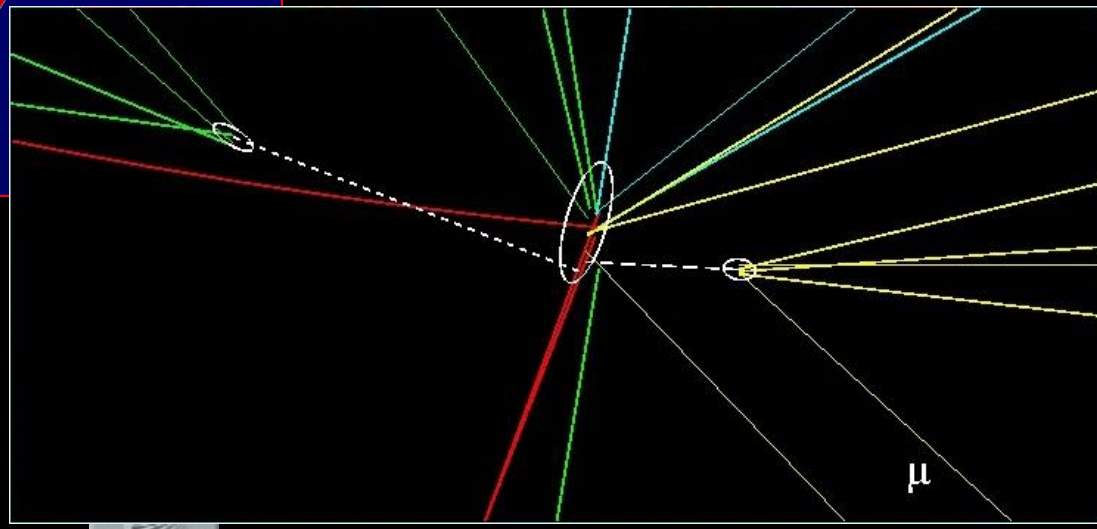
First data above 206 GeV:



First Serious Candidate
(14-Jun-2000, 206.7 GeV)

- Mass 114.3 GeV/c2;
- Good HZ fit;
- Poor WW and ZZ fits;
- P(Background) : 2%
- s/b(115) = 4.6

The purest candidate event ever!



b-tagging
(0 = light quarks, 1 = b quarks)

- Higgs jets: 0.99 and 0.99;
- Z jets: 0.14 and 0.01.

CLRC

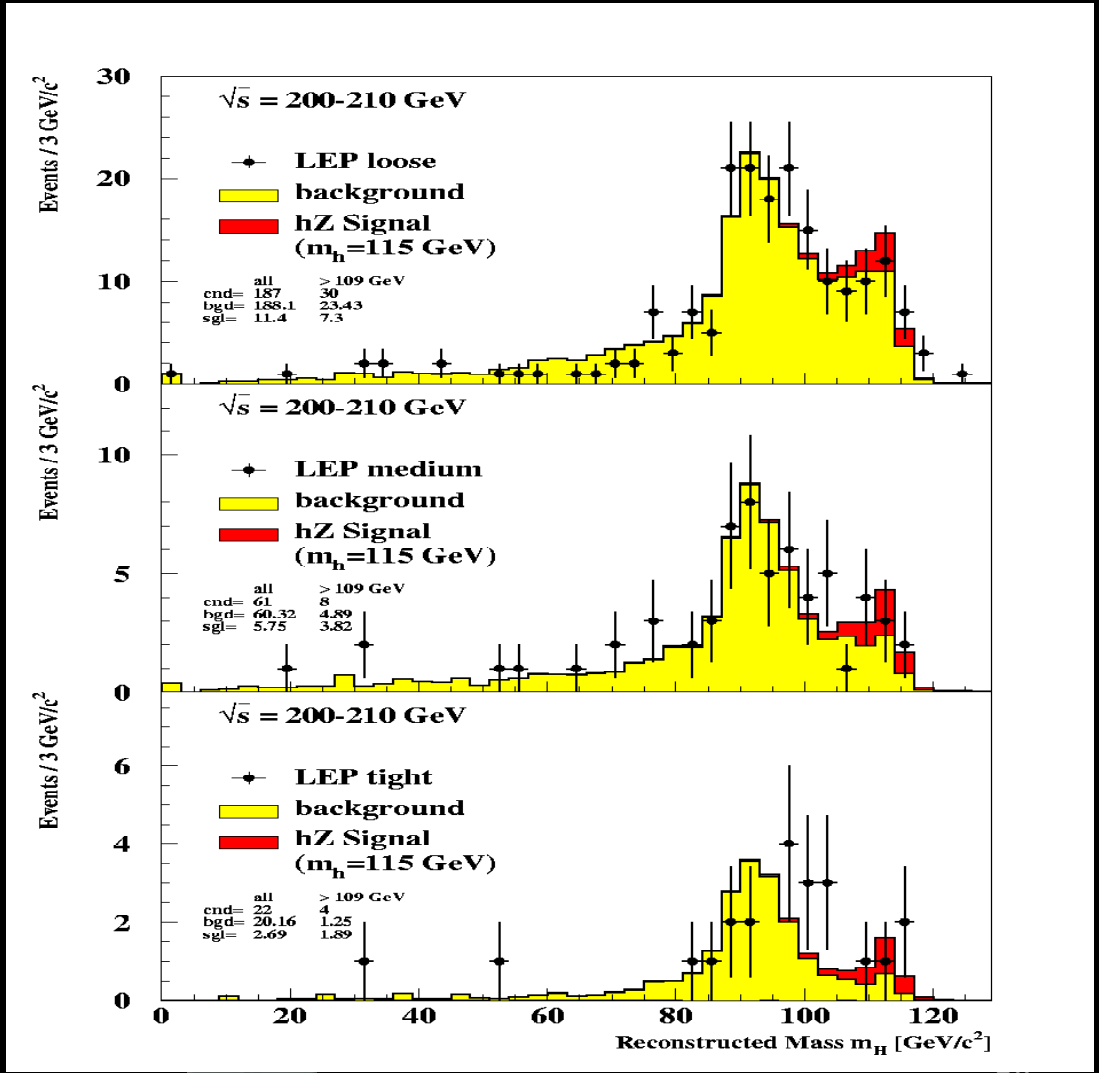
Combined Mass Plot

Distribution of the reconstructed Higgs boson mass with increasing purity for a signal with mass 115 GeV/c^2

Yellow: background

Red: Higgs

Essential to understand the background if we want to claim something new



What is the position?

LEP closed in 2000

- Precision studies of Z,W and top DEMAND a Higgs:
- M_W agrees with Higgs' predictions to 1 per mille,

m_H 53 to 141 GeV/c^2

- Direct Searches (4 in 100 effect)

$m_H = 115.6^{+0.8}_{-0.8}$ GeV/c^2

Is this a coincidence?

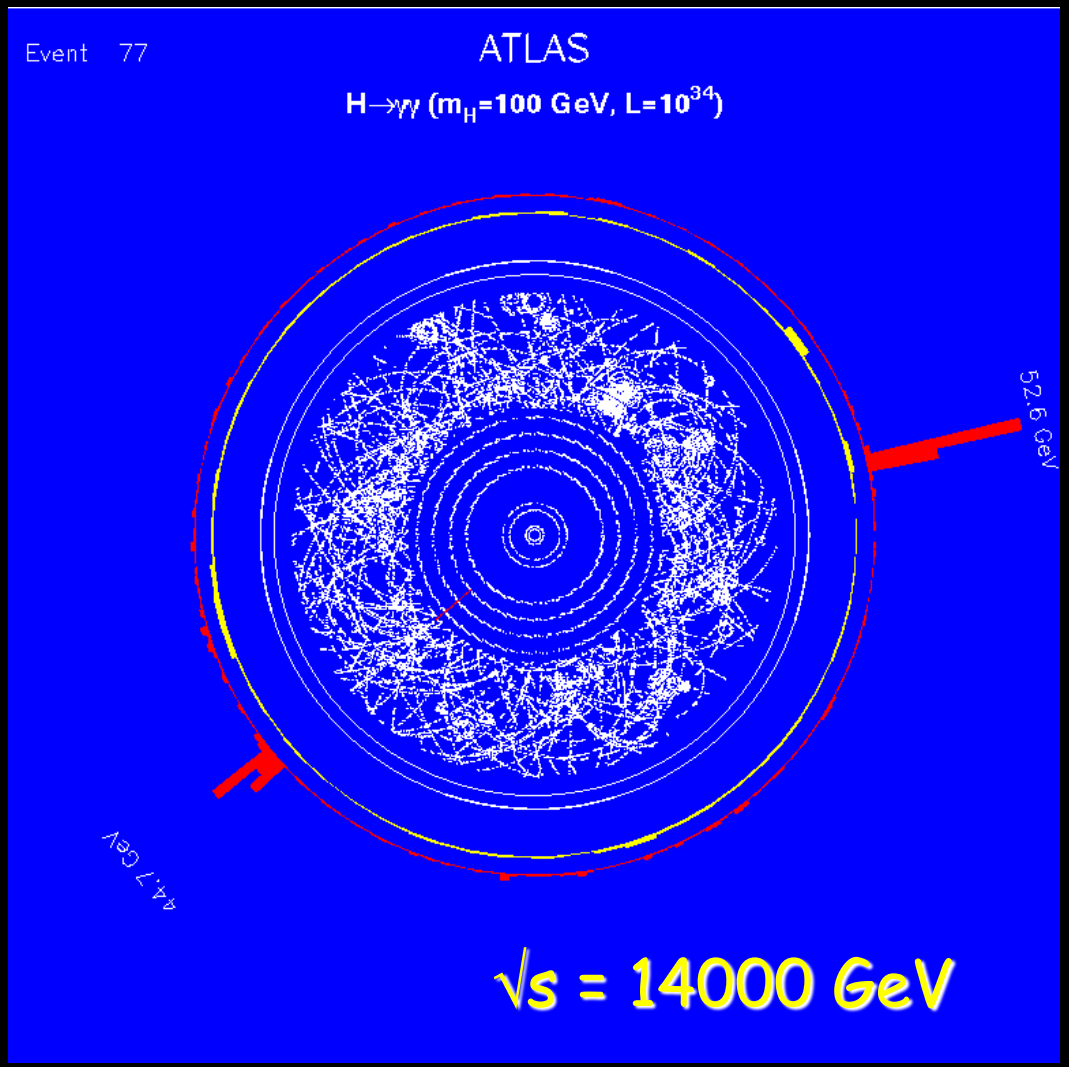
We look to the future to solve this question.

What happens next?

The Tevatron:

- A pp collider, near Chicago;
- run II started in 2001 – collecting far more data than before
- Can probably find a 115GeV Higgs by 2007

What happens next?



The LHC:

- CERN's future **pp collider**;
- Designed to find the Higgs, it can do it!
- First chance in 2007

What happens next?

TESLA:

- A Proposed e^+e^- collider - CLEAN
- 500-800GeV, very high rate
- Find the Higgs in ½ a day: study it carefully

Some Unanswered Questions

- **Does the Higgs exist? If not, how do you explain mass?**
- **Where is all the anti-matter?**
  - **See Stefania's talk**
- **What about Gravity**
  - **Why do we get the cosmological constant wrong by 10^{120}?**
- **Why are there 3 generations of particles? And 3 colours?**