Introduction to the Standard Model

Quarks and leptons

Bosons and forces

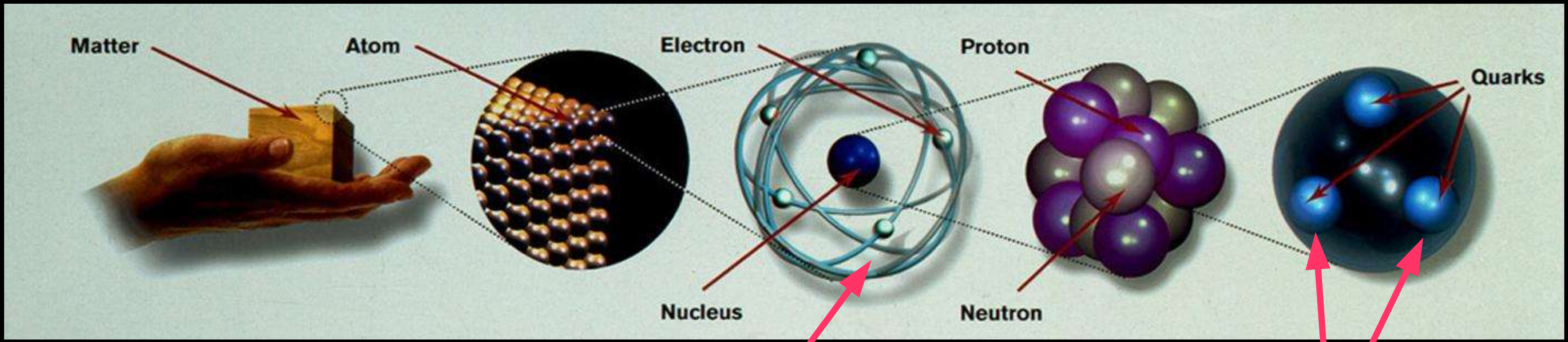
The Higgs

Bill Murray,
RAL,

March 2004

Prepare
Computer
paractical

From you to the quark



Electrons orbiting nucleus

u and d type quarks

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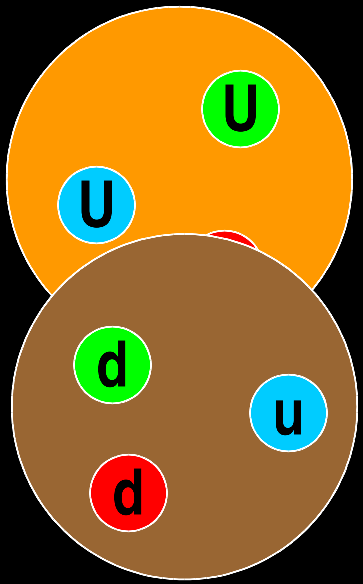
The Matter Particles

Proton



Mass: $1.7\ 10^{-27}$ kg

charge: +1

Neutron

Charge: 0

Electron

Mass: 0.0005 proton mass

charge: -1

Neutrino

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

Charge: 0

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The particles of Matter

u u u — 'up' quark

d d d — 'down' quark

Come in 3 versions, known as colours

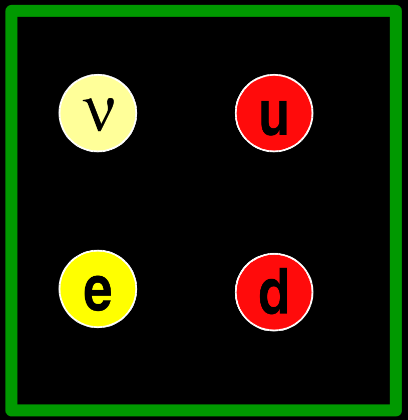
Exercise to check this later

Why 3 colours?

ν — neutrino

e — Electron

The particles of Matter



All ordinary matter is composed of these

There is a corresponding antiparticle for each,
see Bruce's talk later

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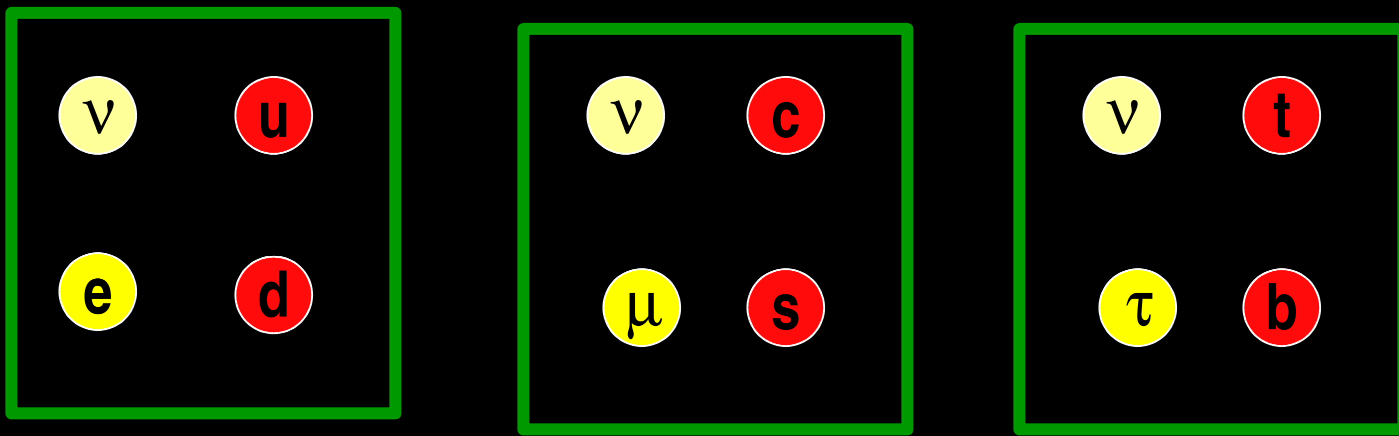
The Matter particles



1st Generation — Ordinary matter

2nd Generation — Cosmic rays

3rd Generation — Accelerators

Why 3 generations ?

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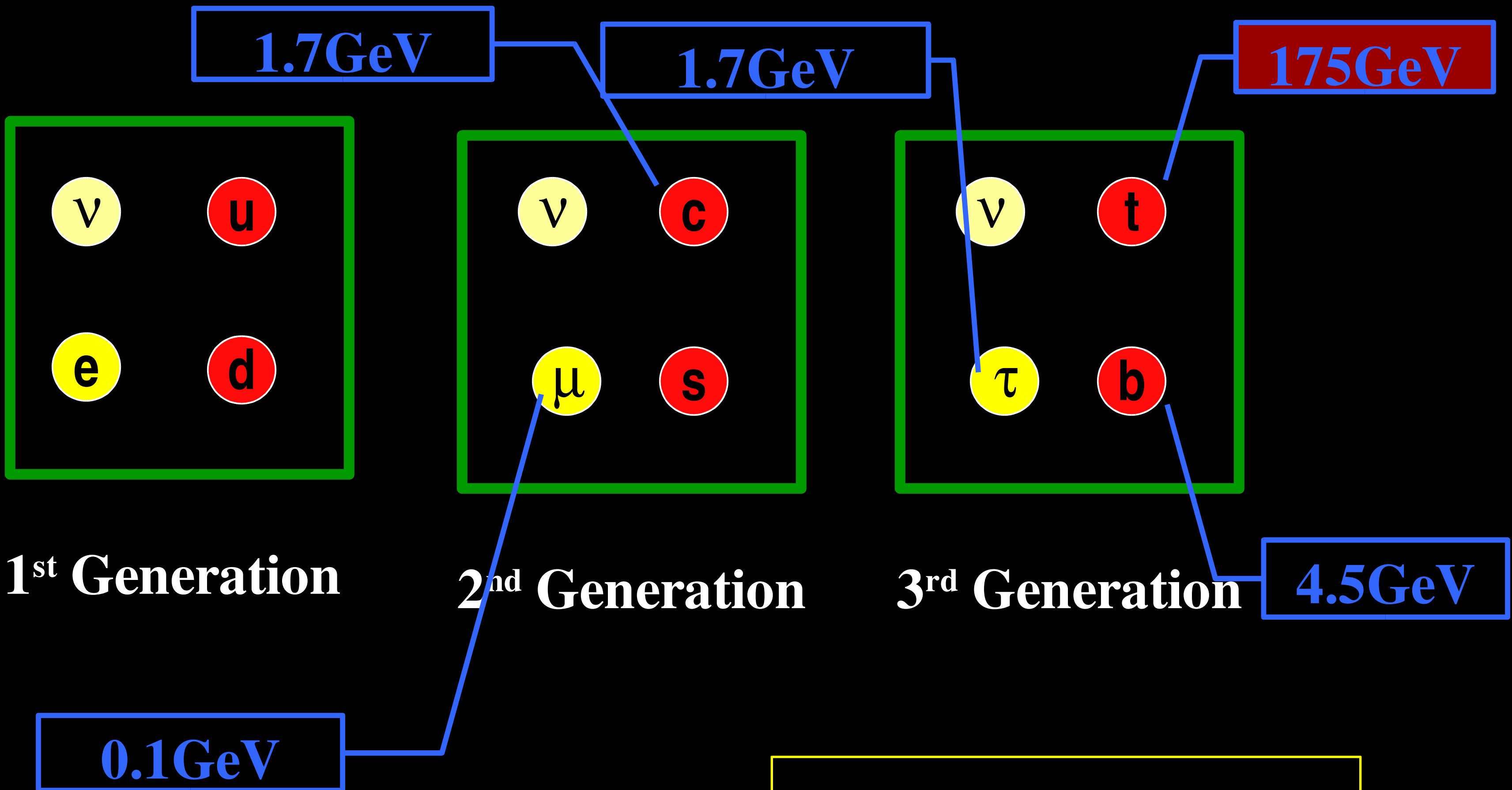
The Matter particles

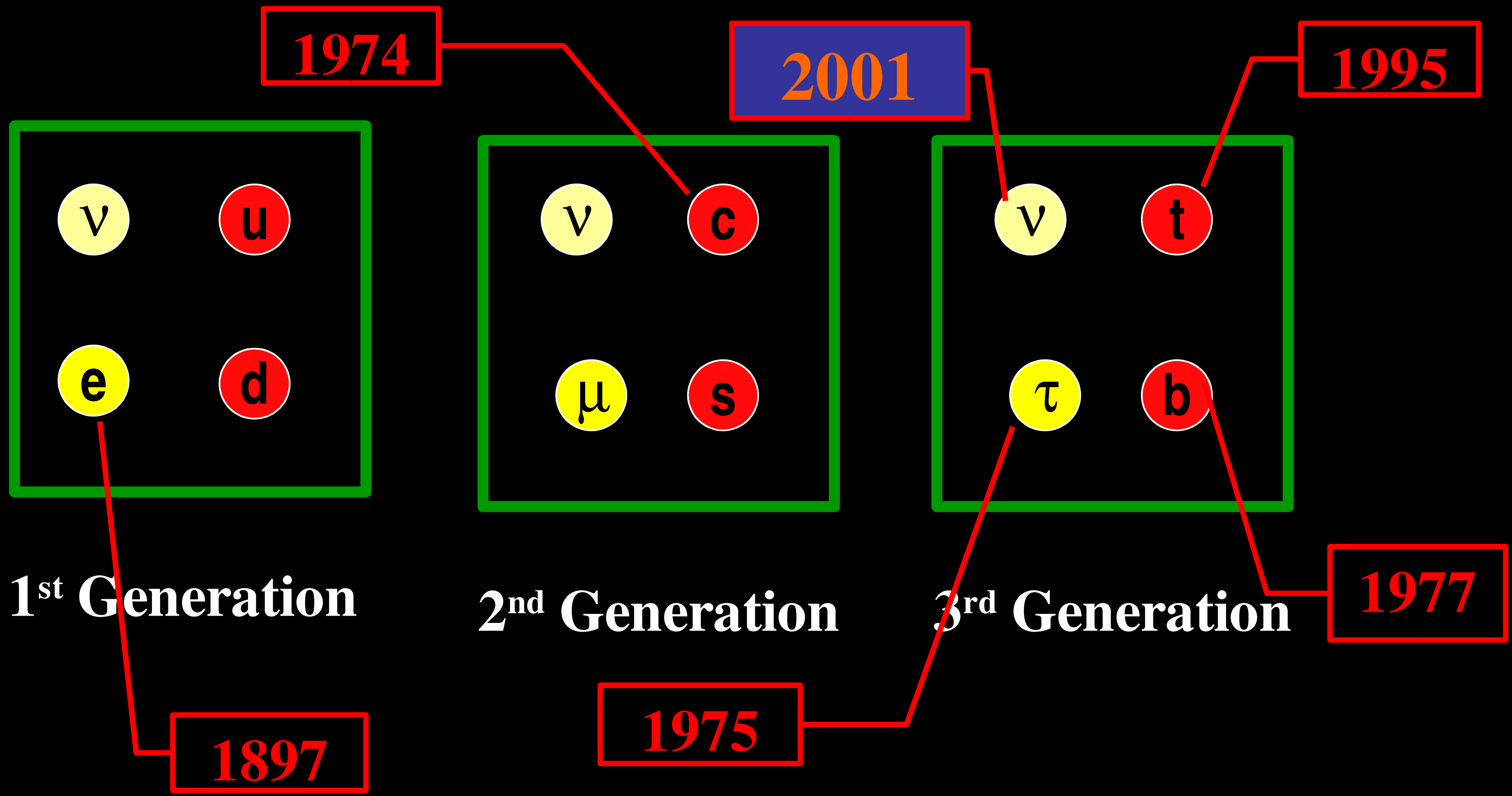


Others are lighter

$$E=mc^2$$

1GeV~Proton Mass

The Matter particles



Are these 'generations' identical?

Almost...not quite

The weak nuclear force can change from one generation to another

Conservation of Energy means that heavy→light dominates

$\tau^- \rightarrow \mu^- \overline{\nu_\mu} \nu_\tau$ **Allowed**

$\mu^- \rightarrow \tau^- \overline{\nu_\tau} \nu_\mu$ **Forbidden**

Soon only light ones left

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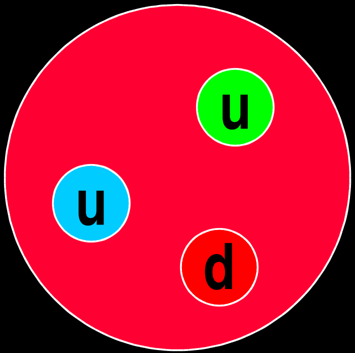
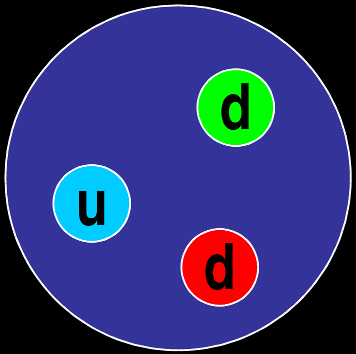
How do quarks combine?



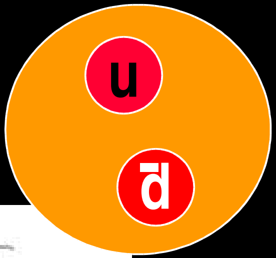
A proton:

two 'u' quarks and one 'd' quark



A neutron:

2 'd' quarks and 1 'u' quark



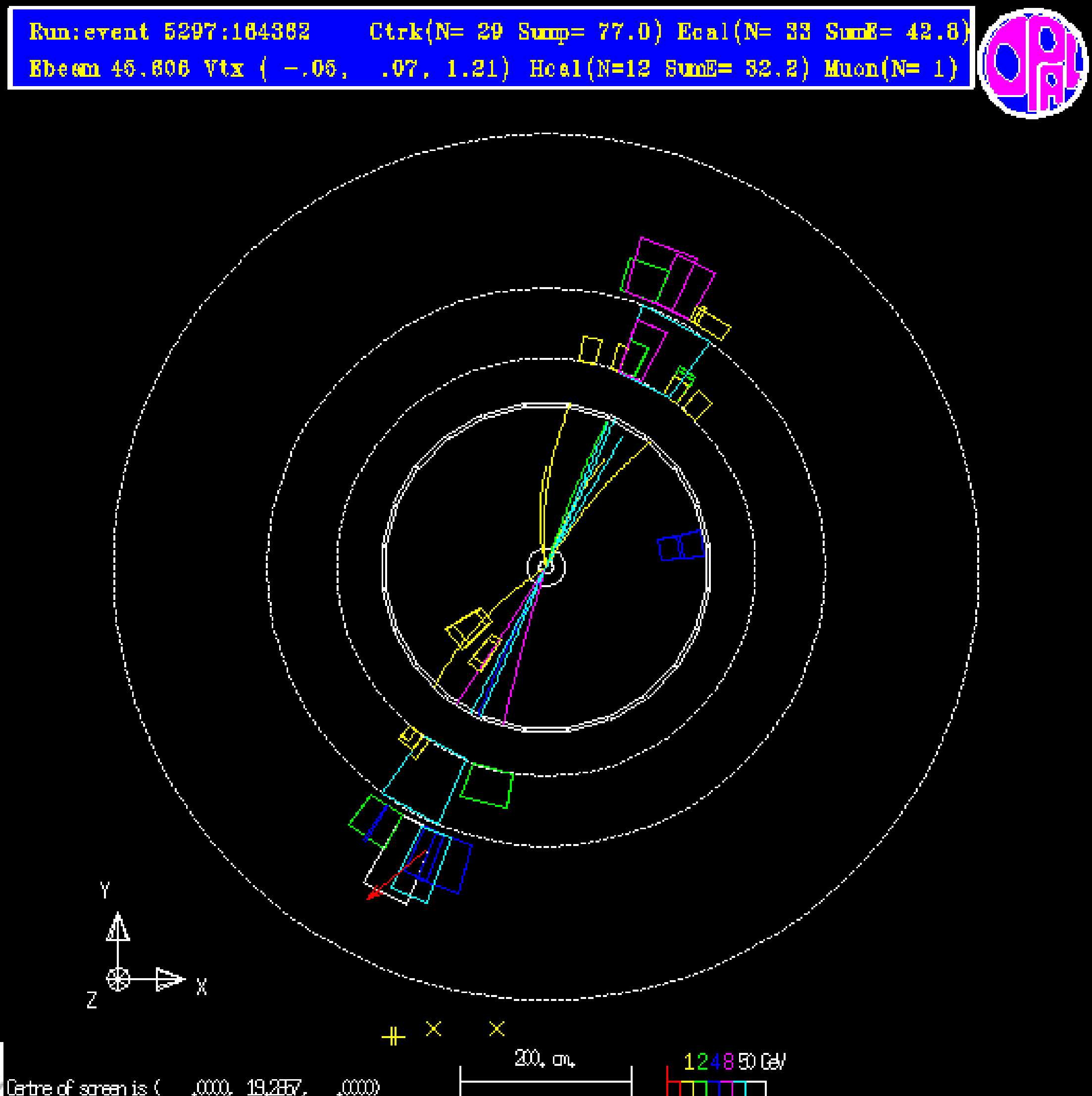
Mesons have a quark and an anti-quark

Only 'colourless' combinations exist:

red + blue + green = white

red + anti-red = black

Can we see a quark?

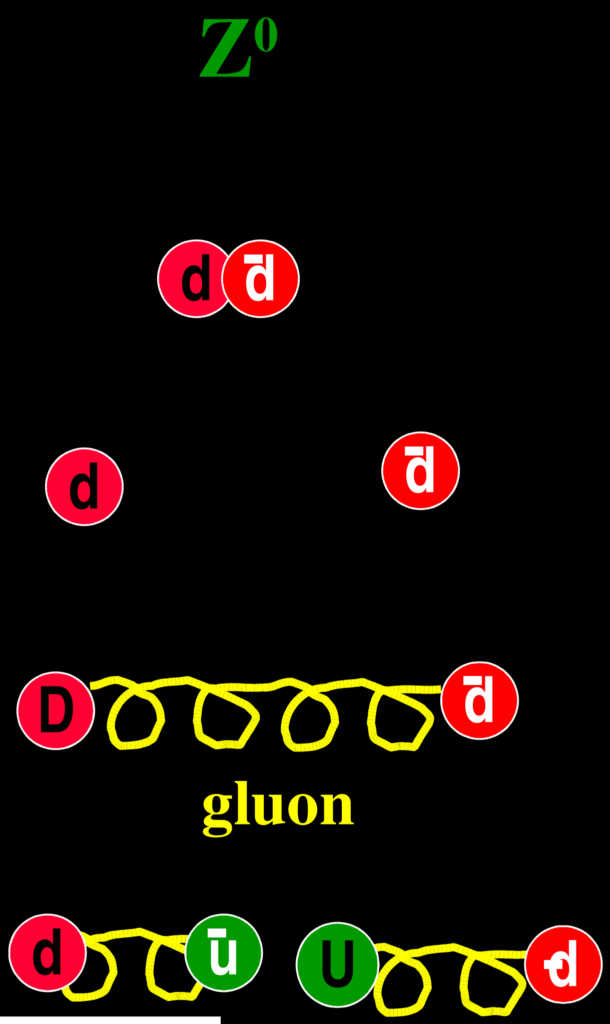


Probably not

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

How do the quarks hide?



Start with a Z

Decays to quarks: close together

- Colours cancel

As they move apart a colour dipole appears

Gluons link the charges together

When gluons snap, new quarks appear

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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 Forces of Nature

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

Higgs may give a link?

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The Forces of Nature

Force	Mass, GeV	Particle
Electro-magnetism	0	Photon, γ
Strong	0	Gluon, g
Weak	80, 91	W^+, W^-, Z^0
Gravitation	Not in the same framework	

γ. g and Z are own antiparticles

W^+ and W^- antiparticles

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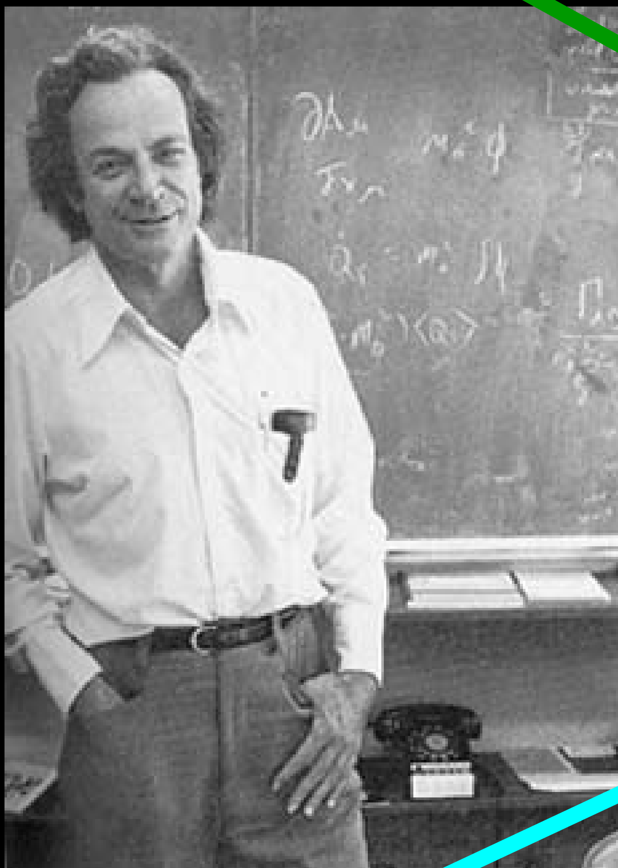
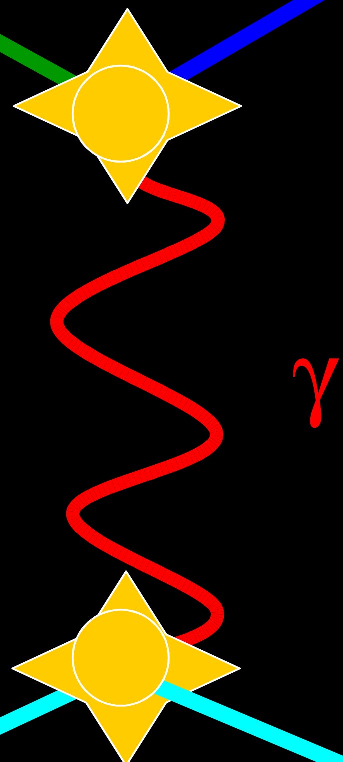
Mediation of the Forces

Electron





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

Positron (anti-electron)

Feynman Diagram

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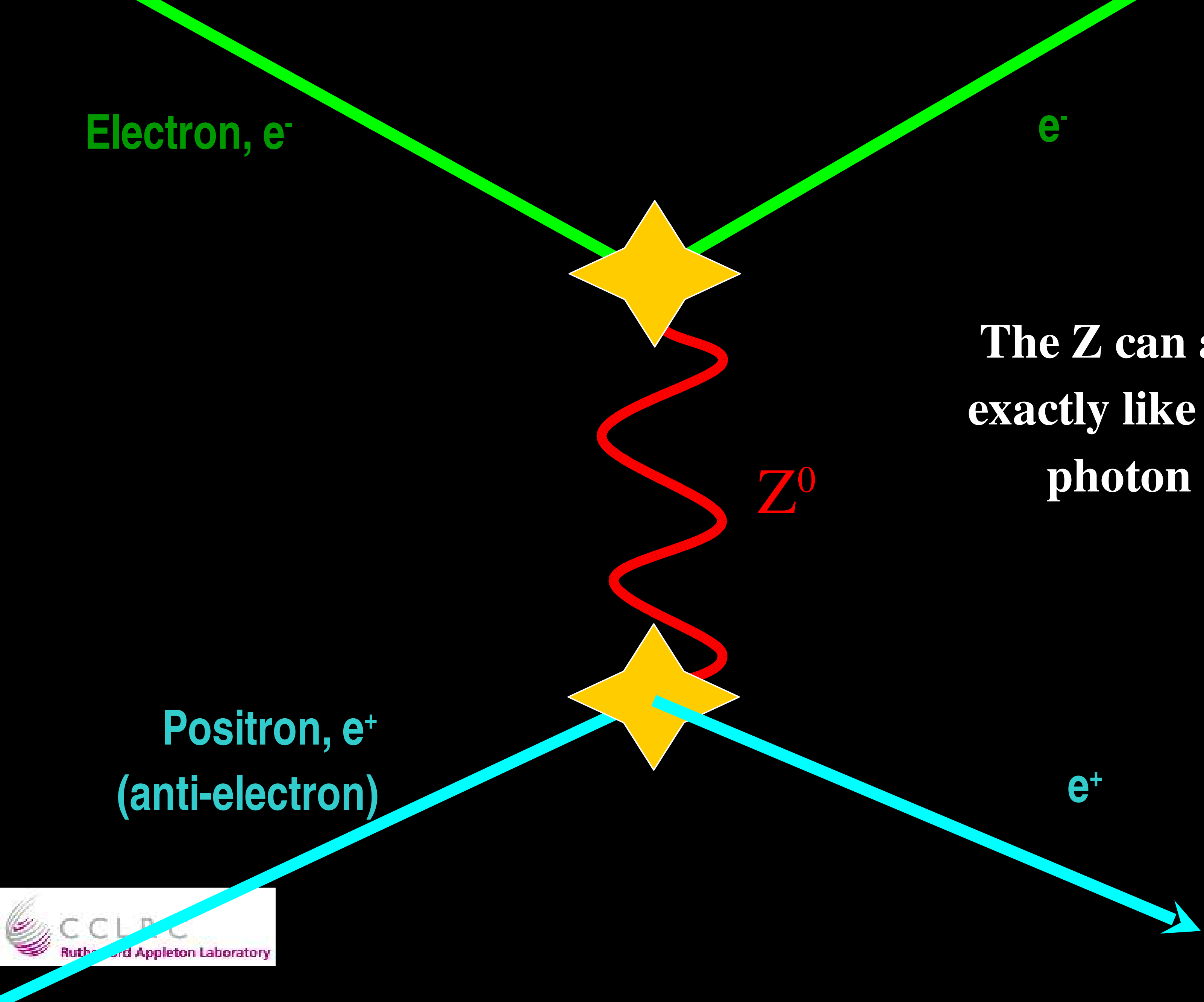
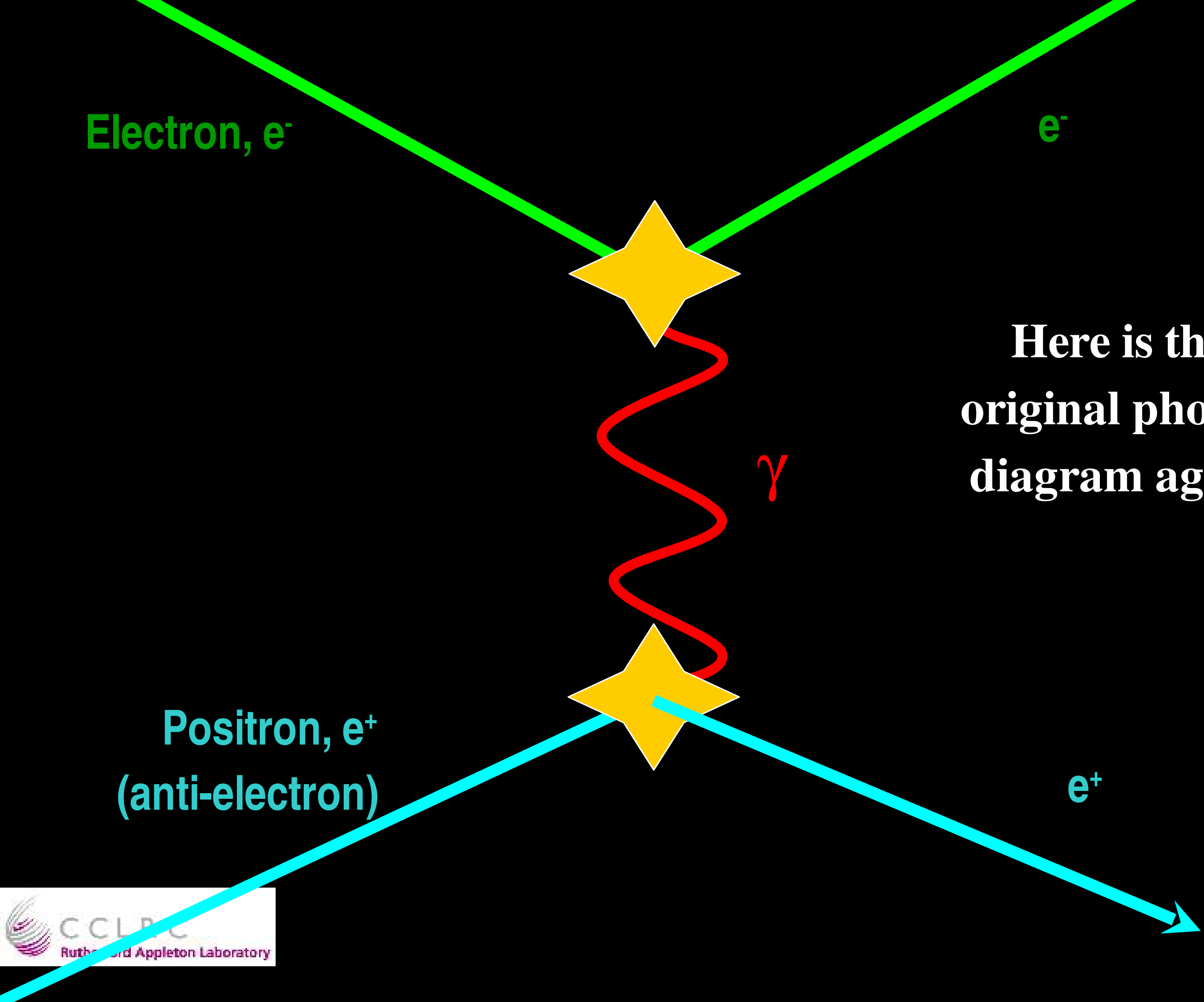
How do W and Z behave?



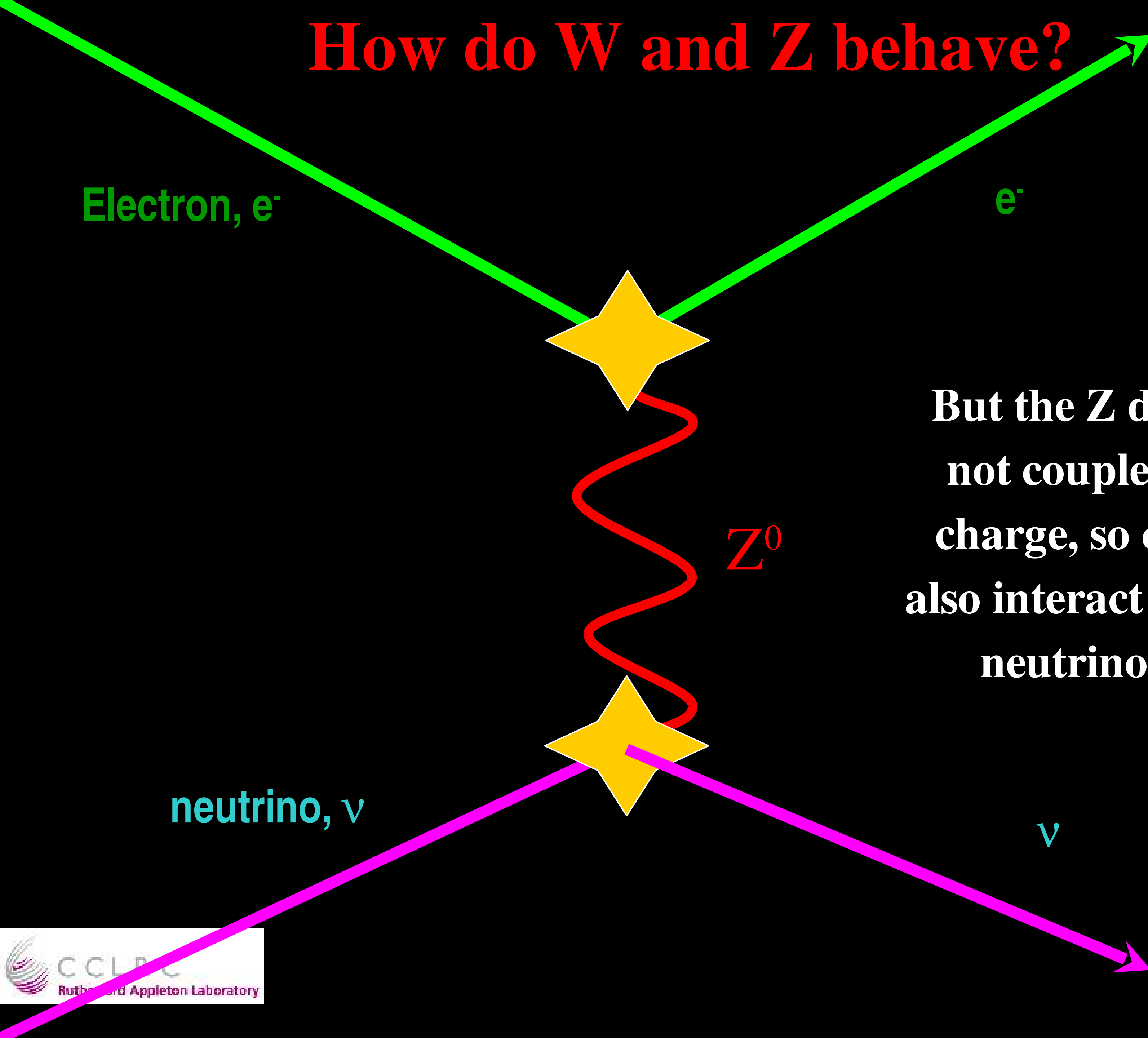
The Z can act exactly like the photon

How do W and Z behave?



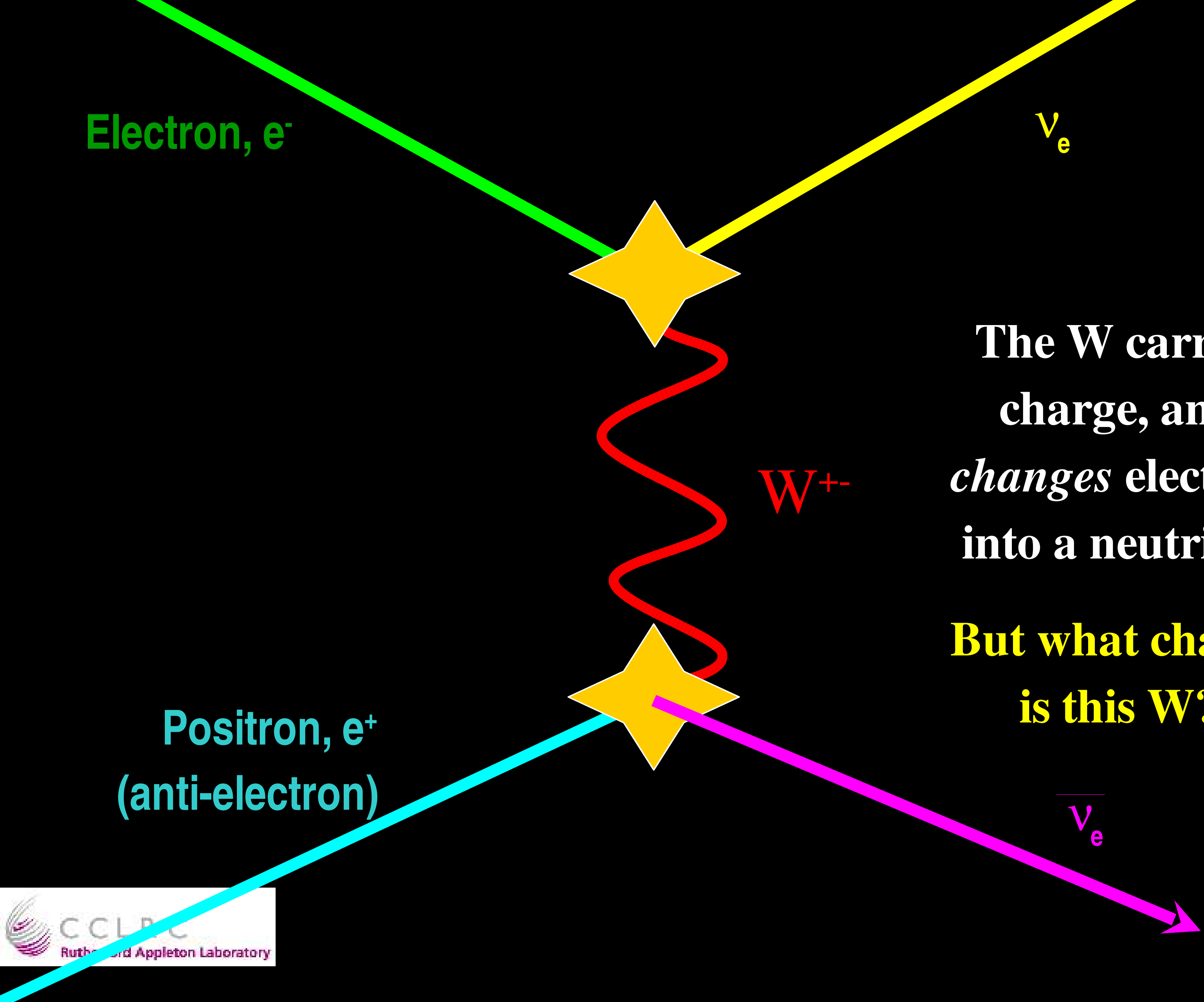
Here is the original photon diagram again

How do W and Z behave?



But the Z does not couple to charge, so can also interact with neutrinos

How do W and Z behave?



The W carries charge, and *changes* electron into a neutrino.

But what charge is this W?

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

Colour is the *charge* of the Strong force

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:

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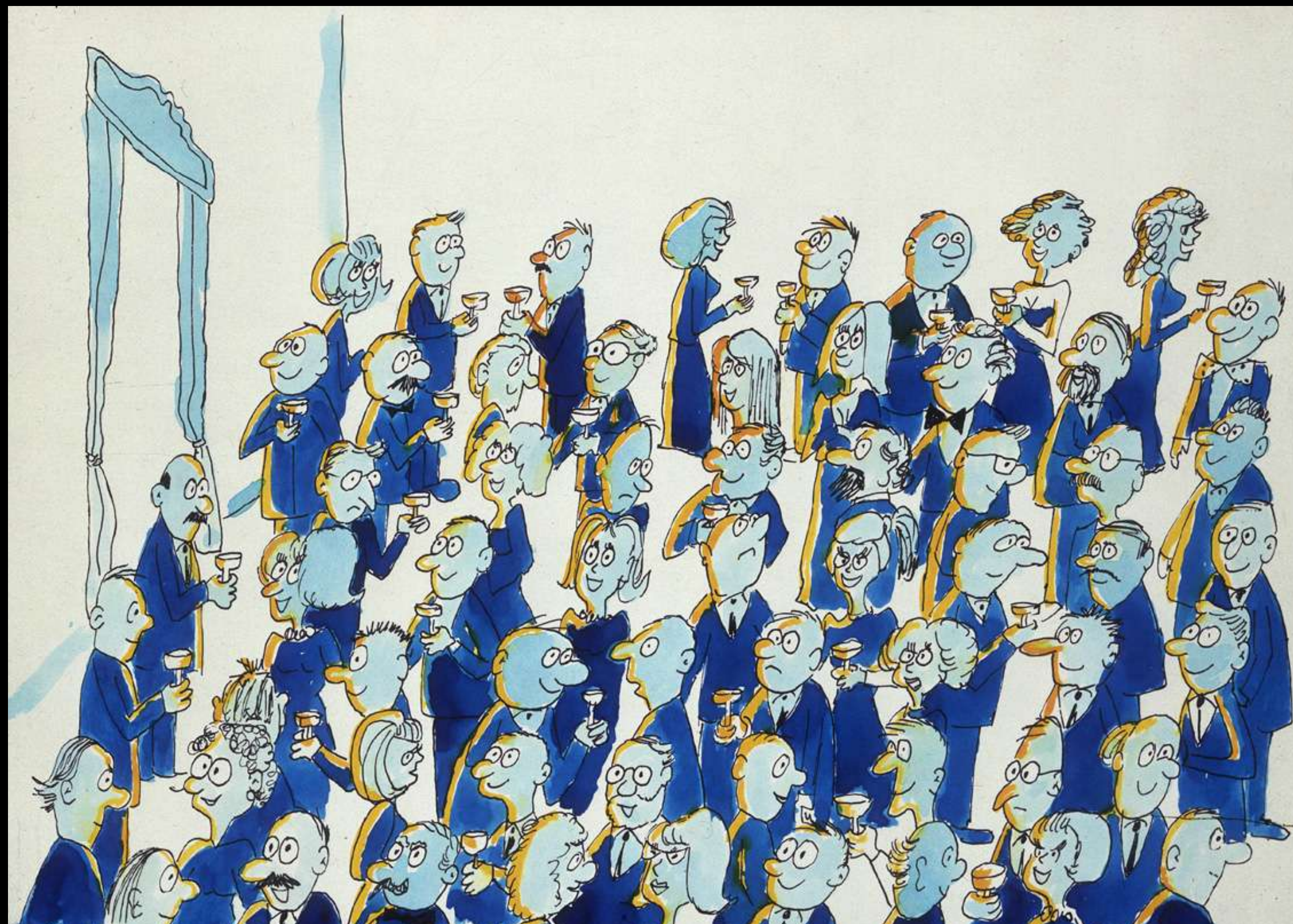
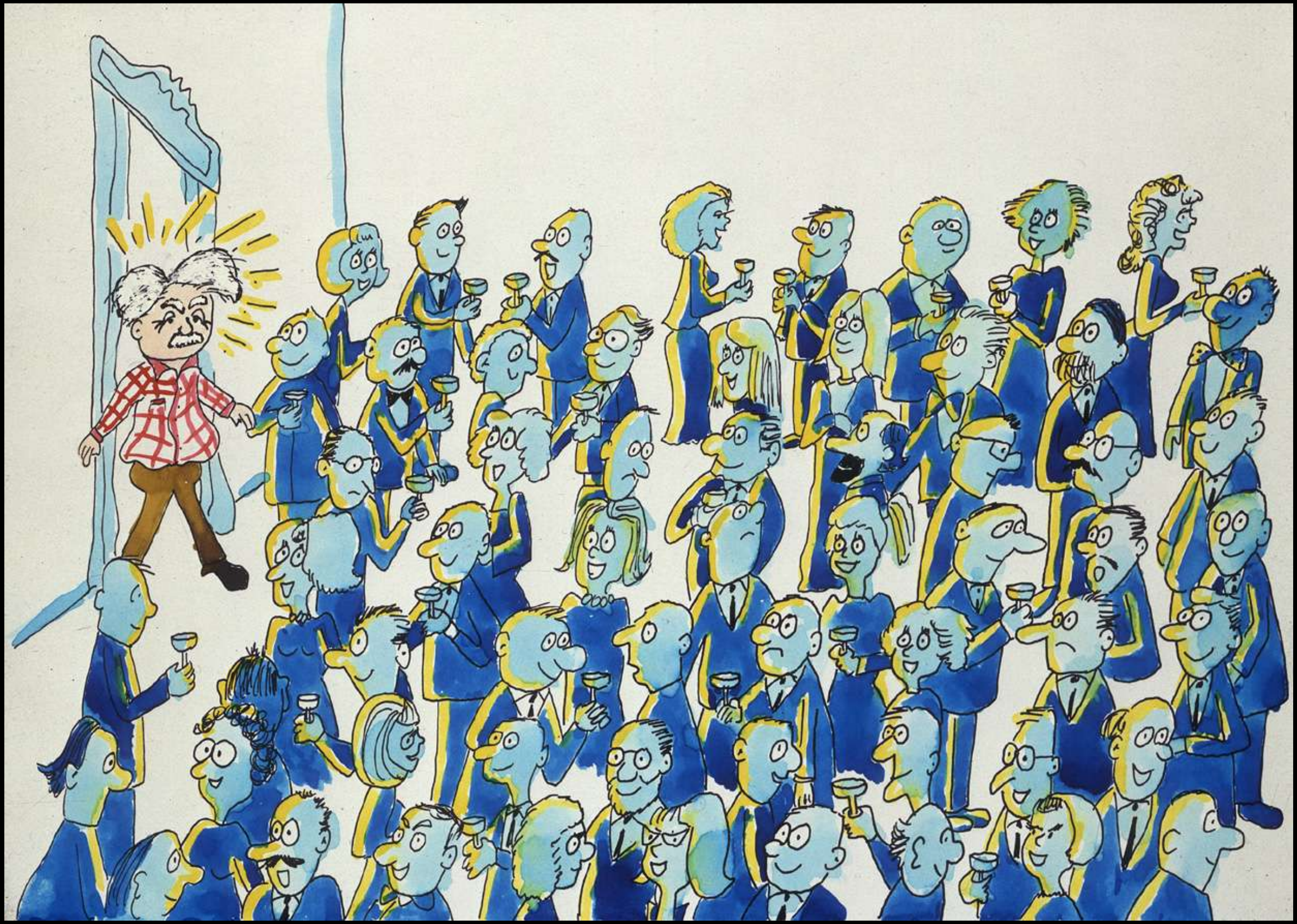
The Waldegrave Higgs challenge



Imagine a room full of
litical activists

The Waldegrave Higgs challenge



The Prime Minister

walks in

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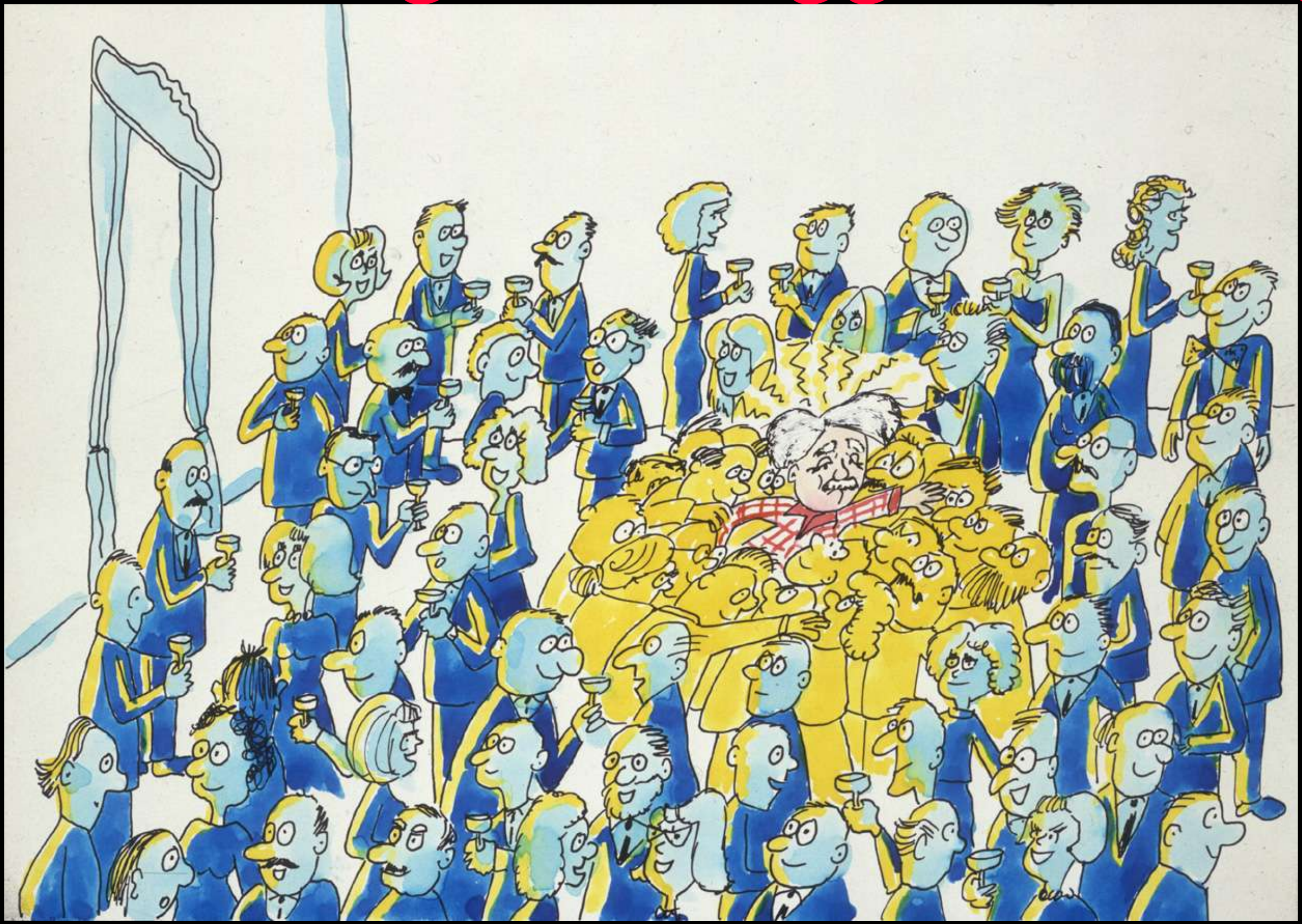
The Waldegrave Higgs challenge



He is surrounded by a
uster 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

Soon we have a cluster of people discussing it

Analogous to Higgs boson

What does Higgs theory imply?

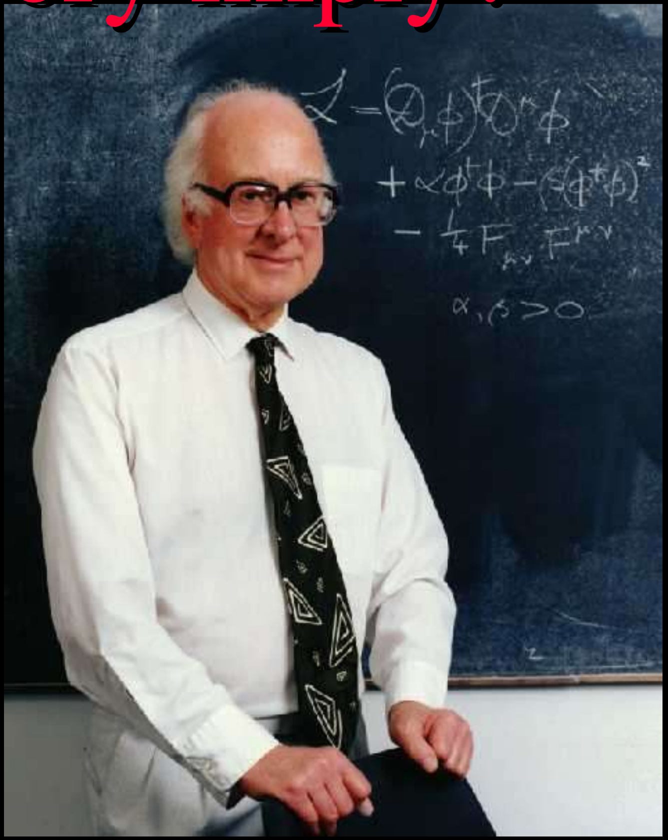
Higgs' mechanism gives mass to W and Z bosons, and to the matter particles.

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

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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

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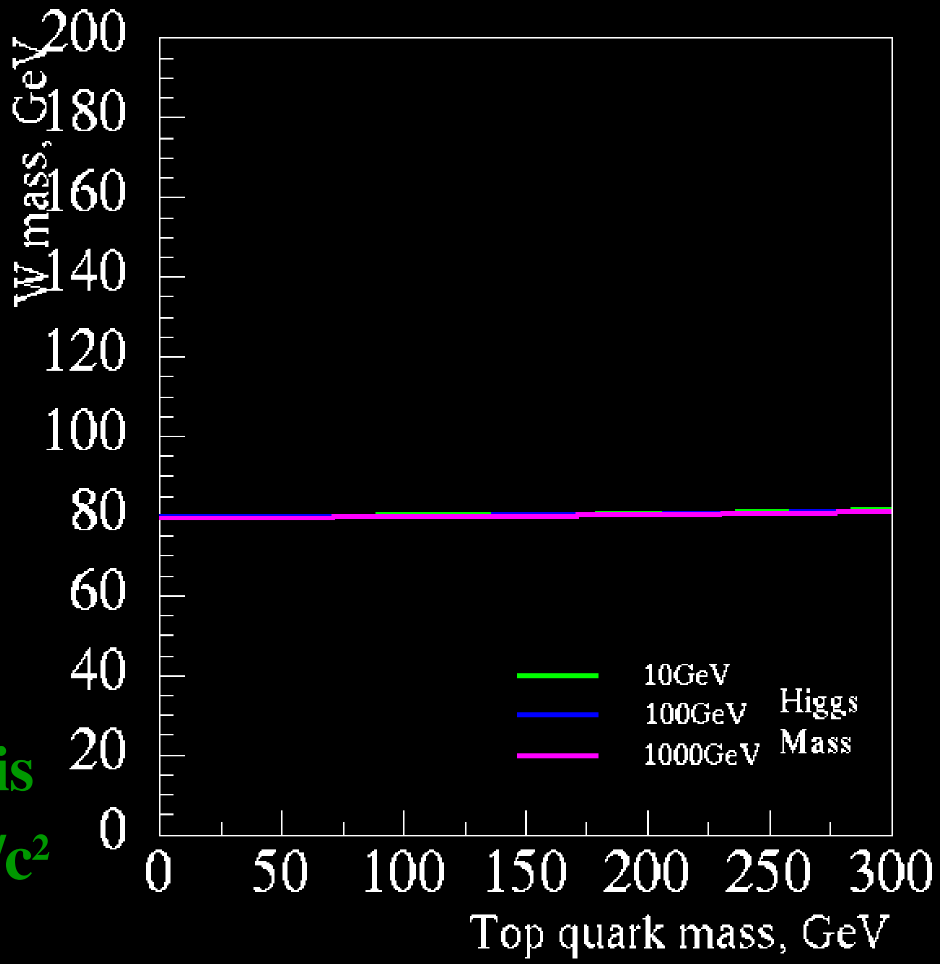
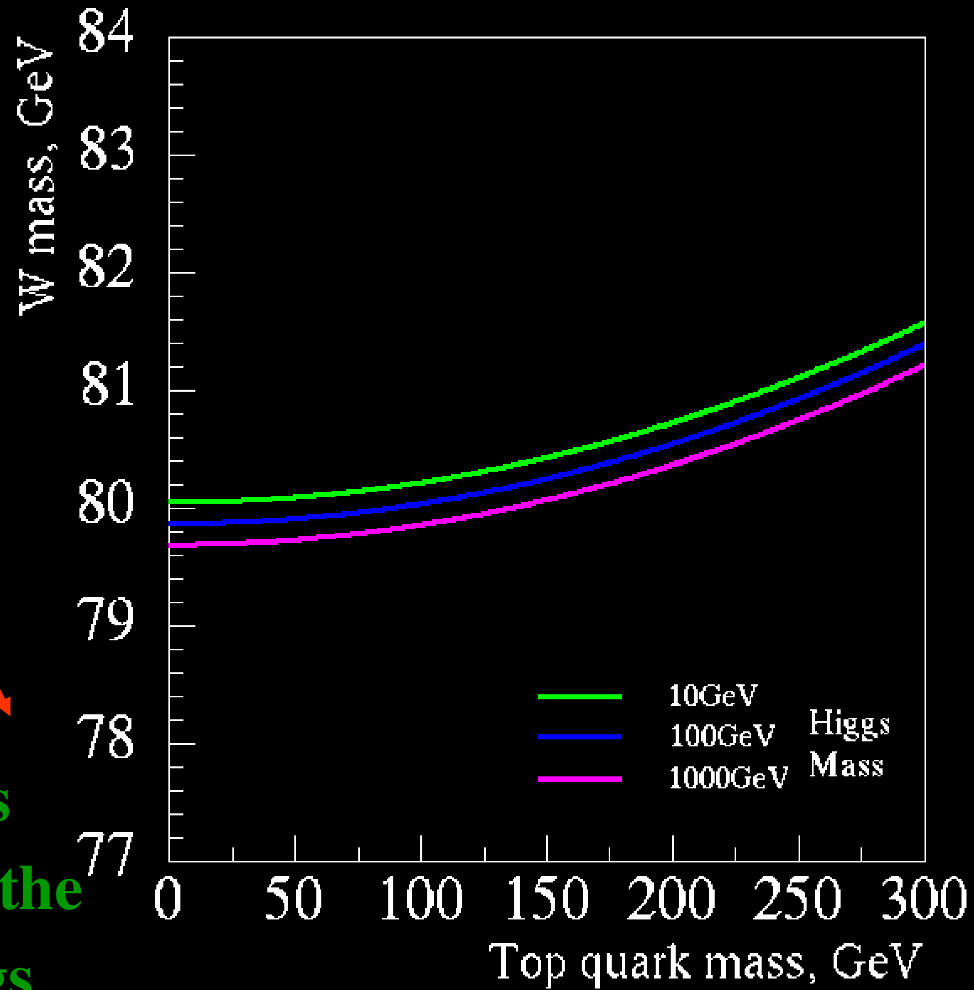
The W, the top quark and Higgs



The W mass is about 80GeV/c²

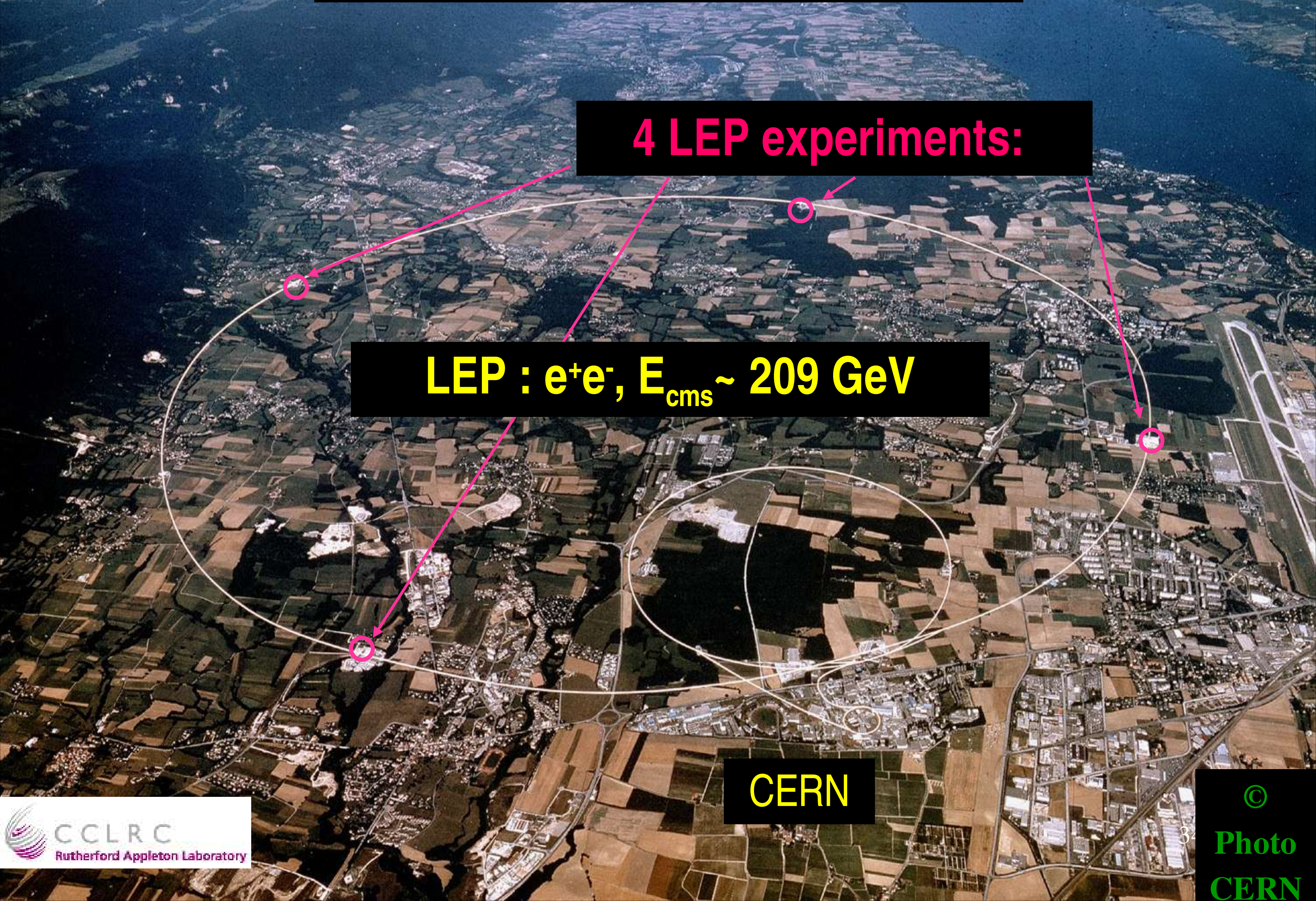
The W, the top quark and Higgs

Expanded scale



The W mass depends upon the top and Higgs masses

CERN's Collider ring



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In the LEP tunnel

27km of vacuum pipe and bending magnets

One LEP experiment: OPAL

One of four rather similar detectors

Assembly in 1989

Note the people

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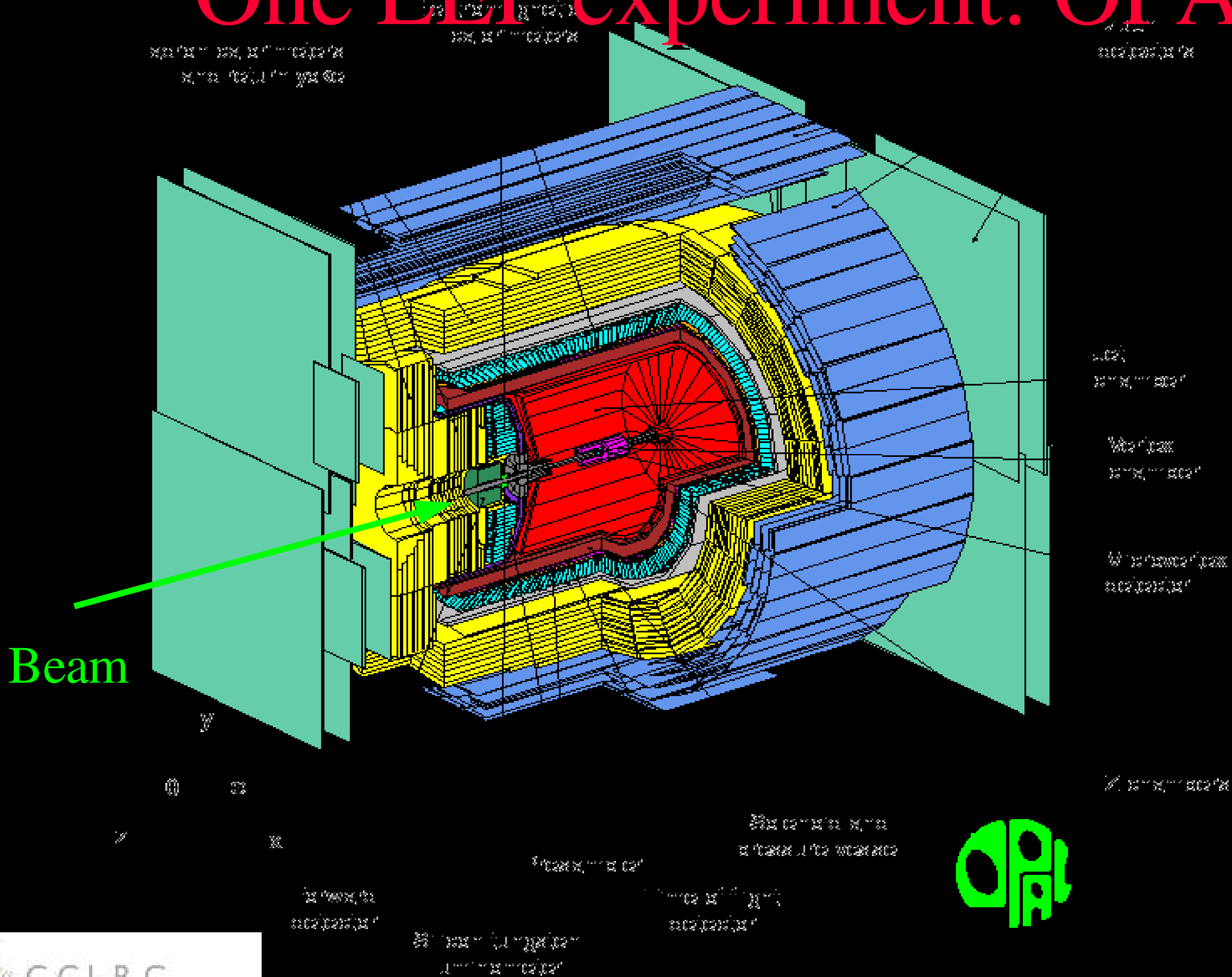
One LEP experiment: OPAL



Cut away view

Onion layers of detectors surround interaction point

Part of OPAL: Tracking Chamber

159 Wires

24 of these sectors make a barrel shape

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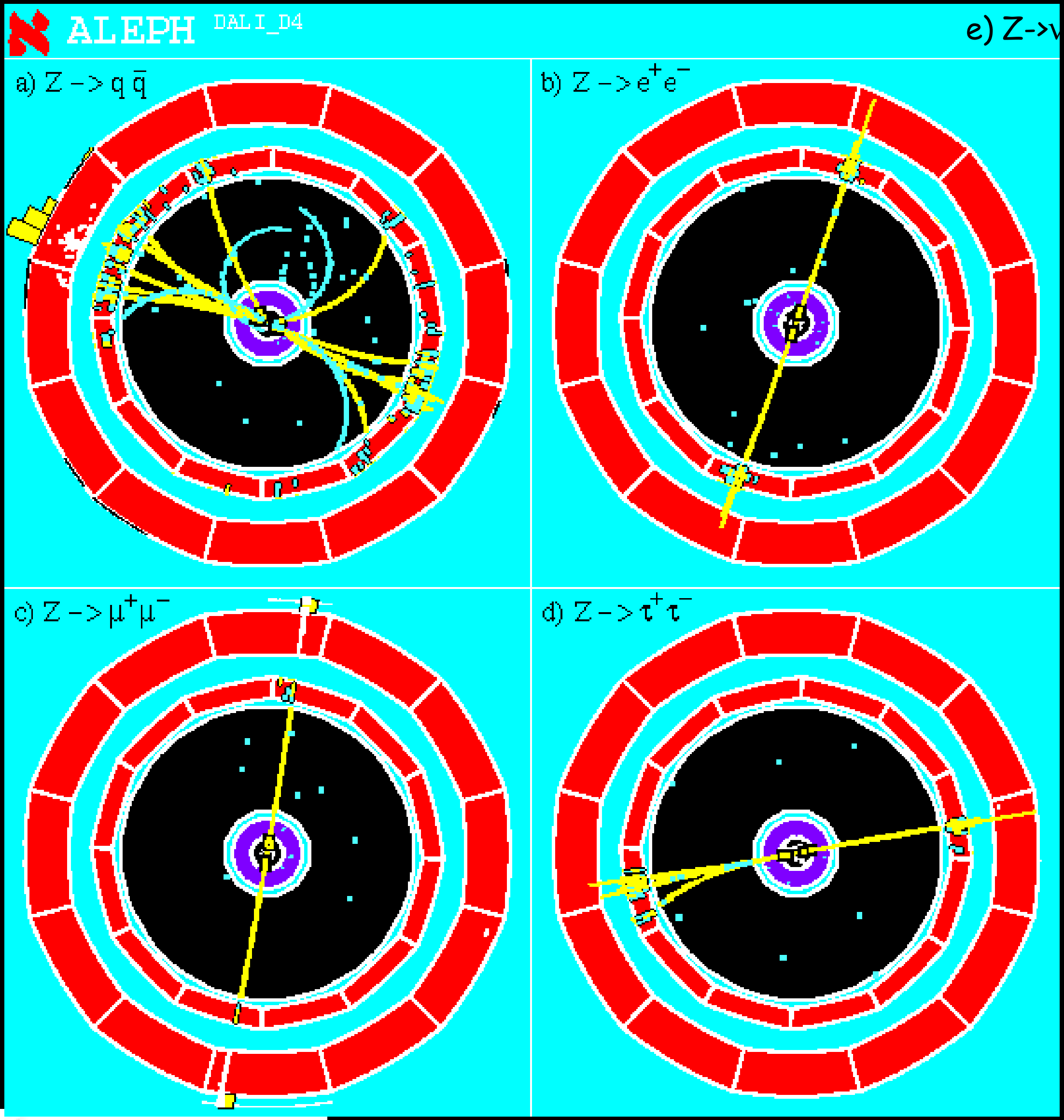
How to recognize events:

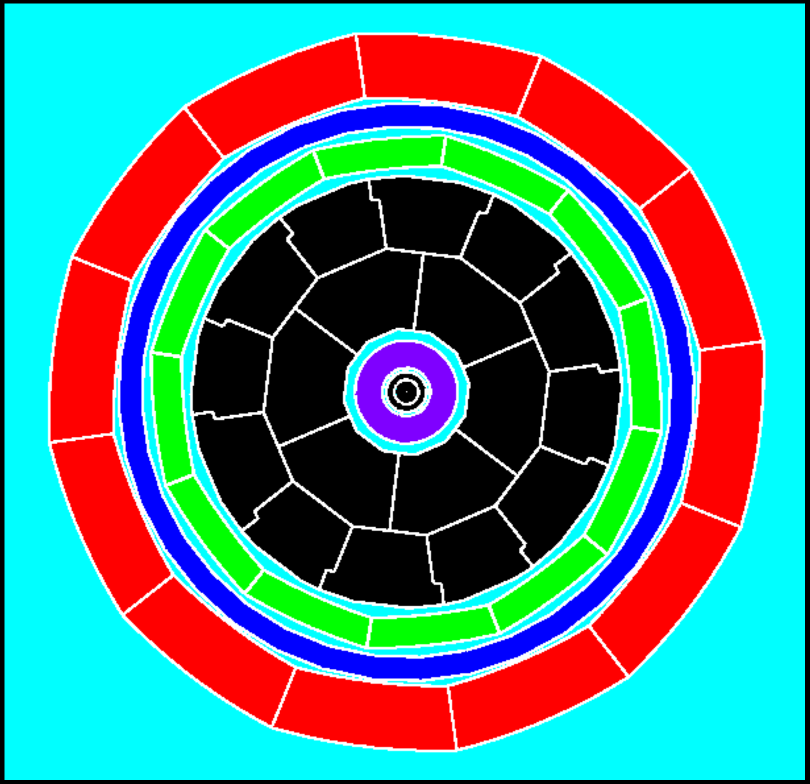


$Z \rightarrow q\bar{q}$: **Two jets, many particles**

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

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

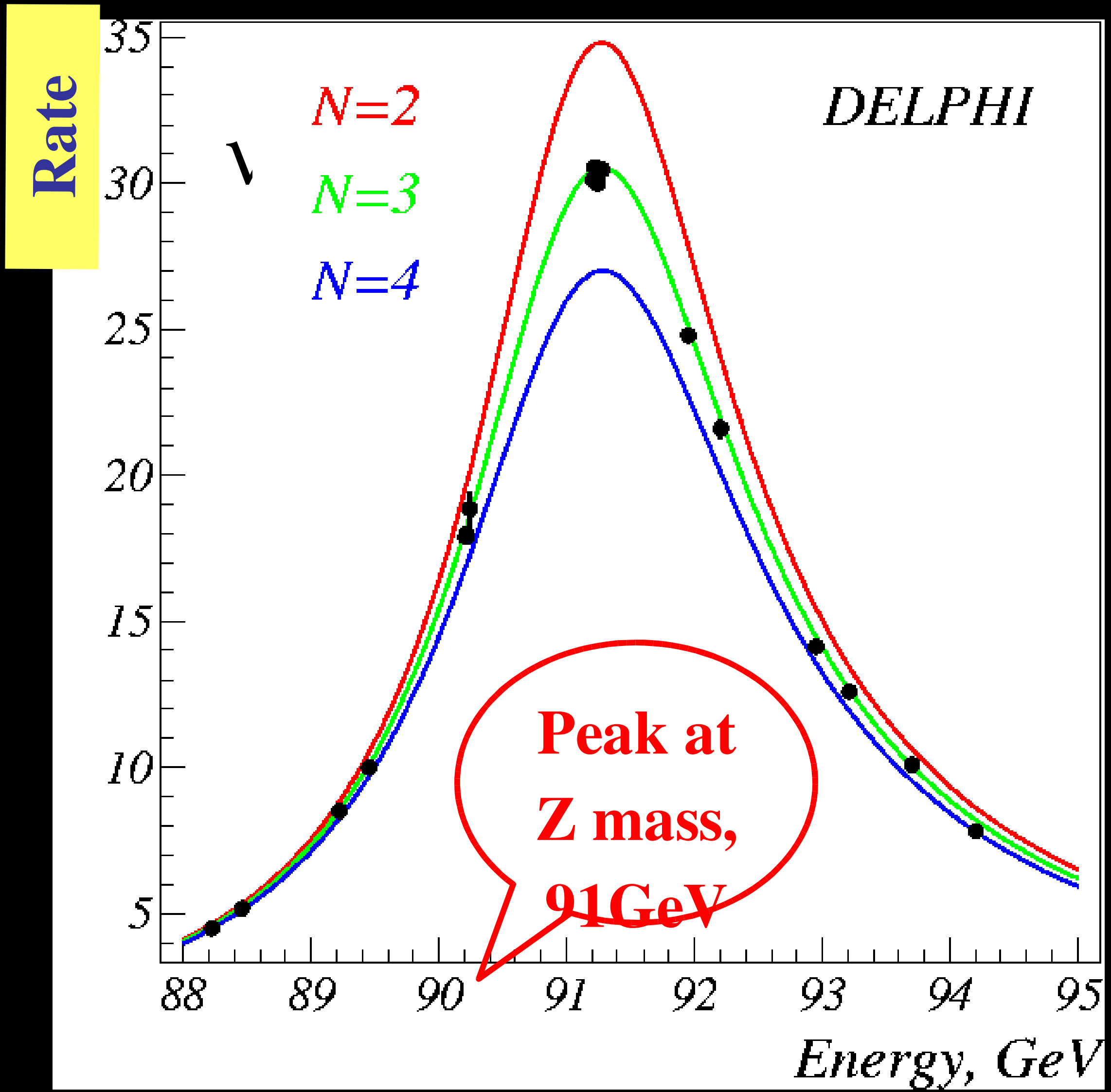
How to recognize Z decays:



$Z \rightarrow \nu\nu$:

Not detectable.

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

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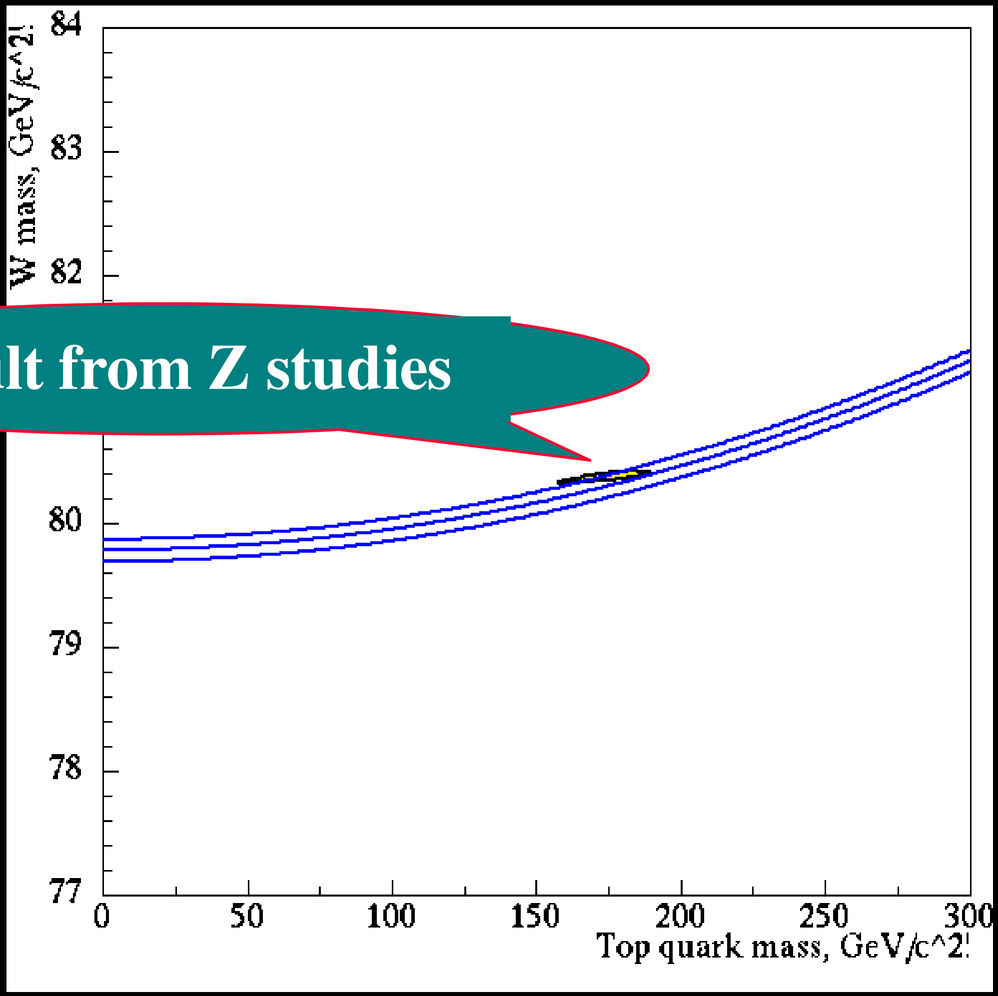
The W, the top quark and Higgs

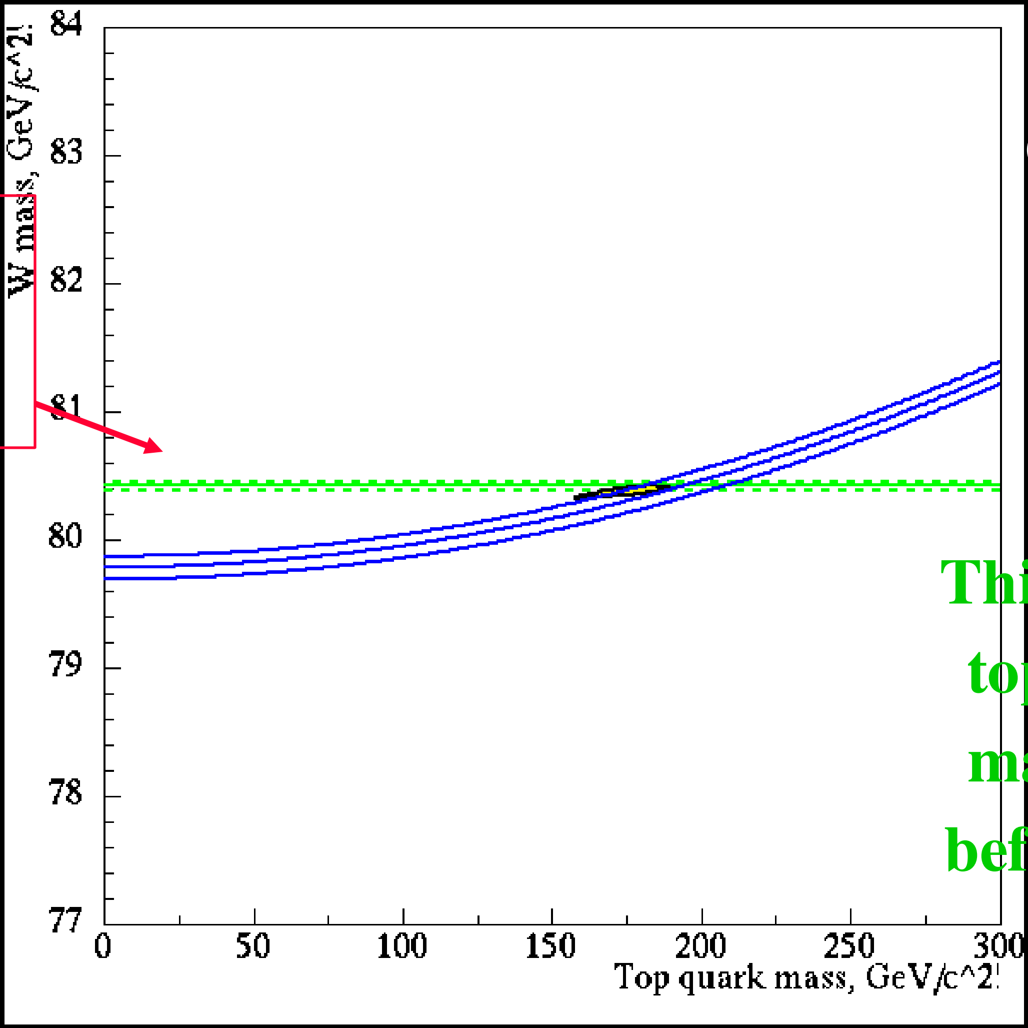


The W and top masses from Z studies agree with theory

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

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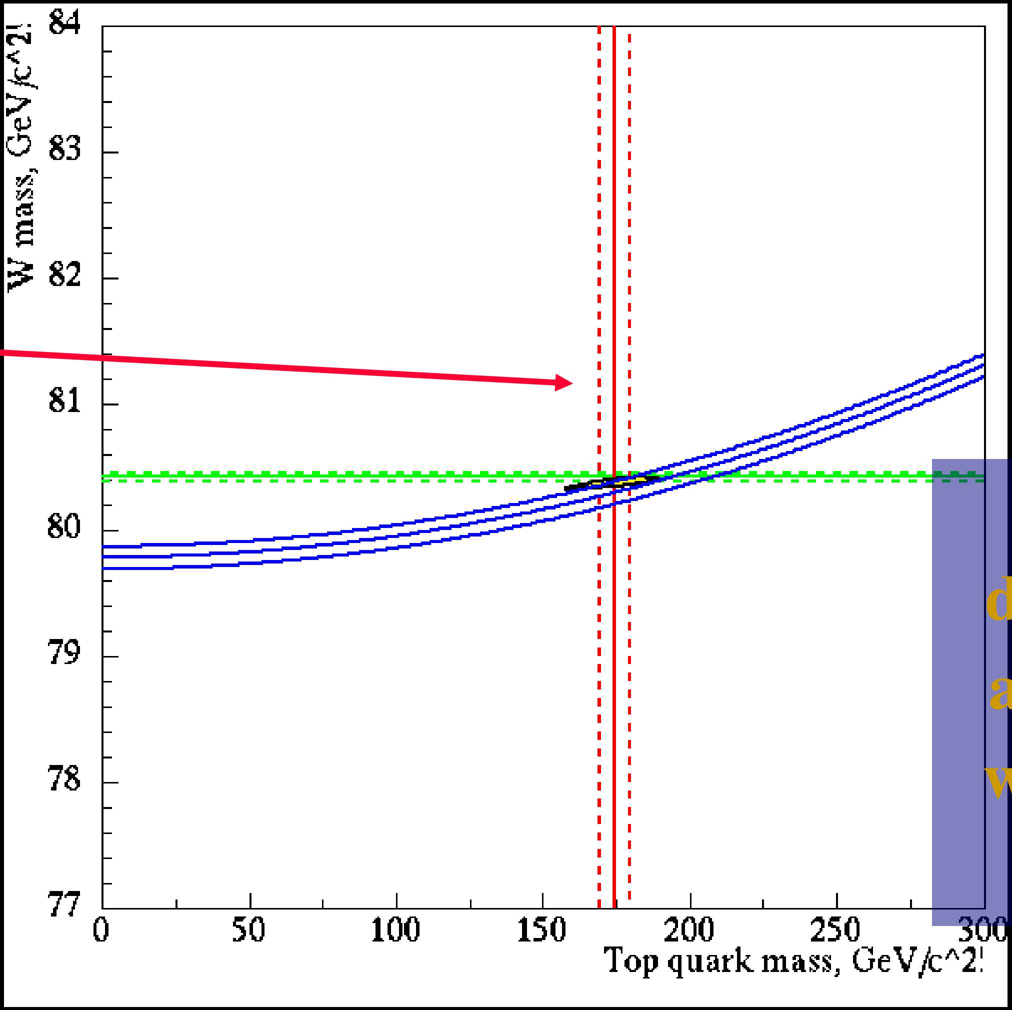
The W, the top quark and Higgs

Top mass from Tevatron

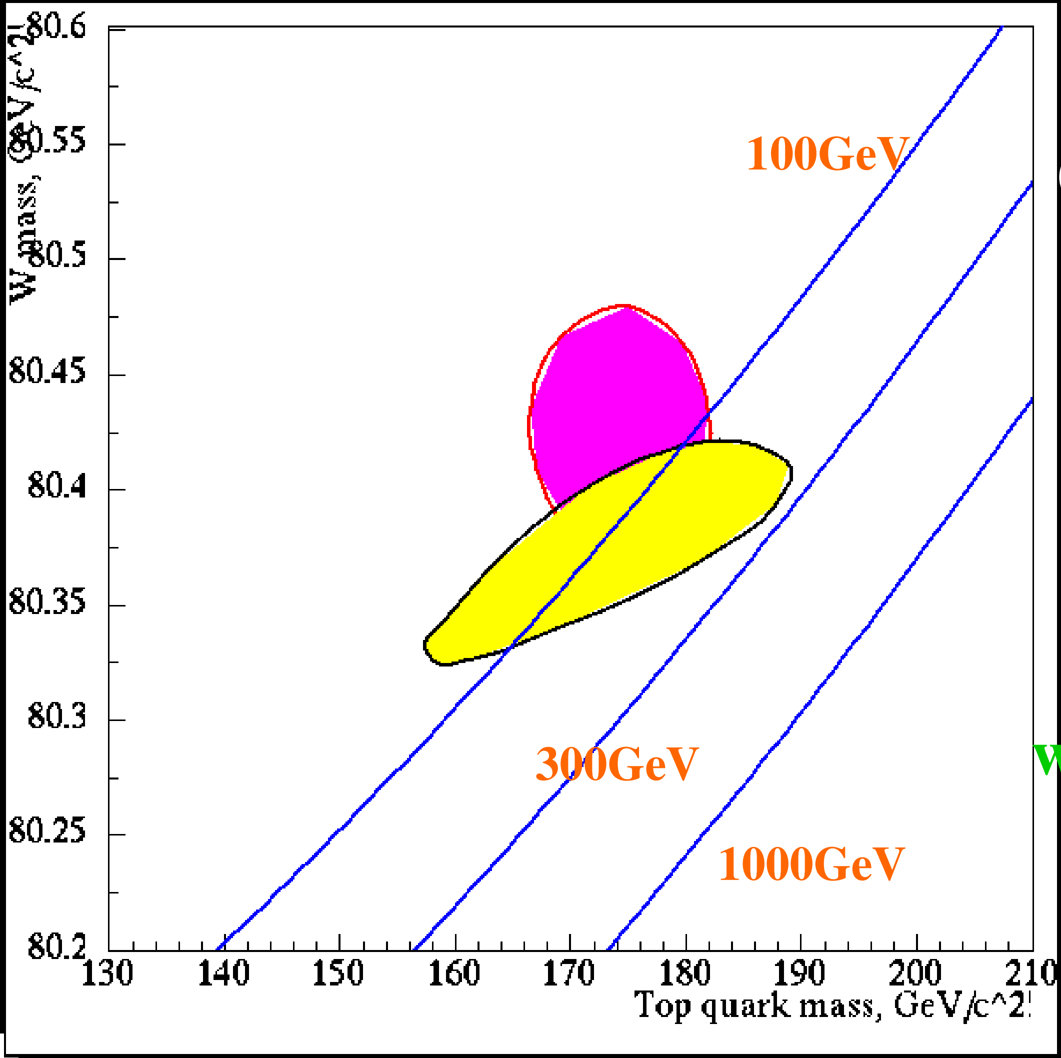


Again, incredible consistency

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 predict Higgs mass?

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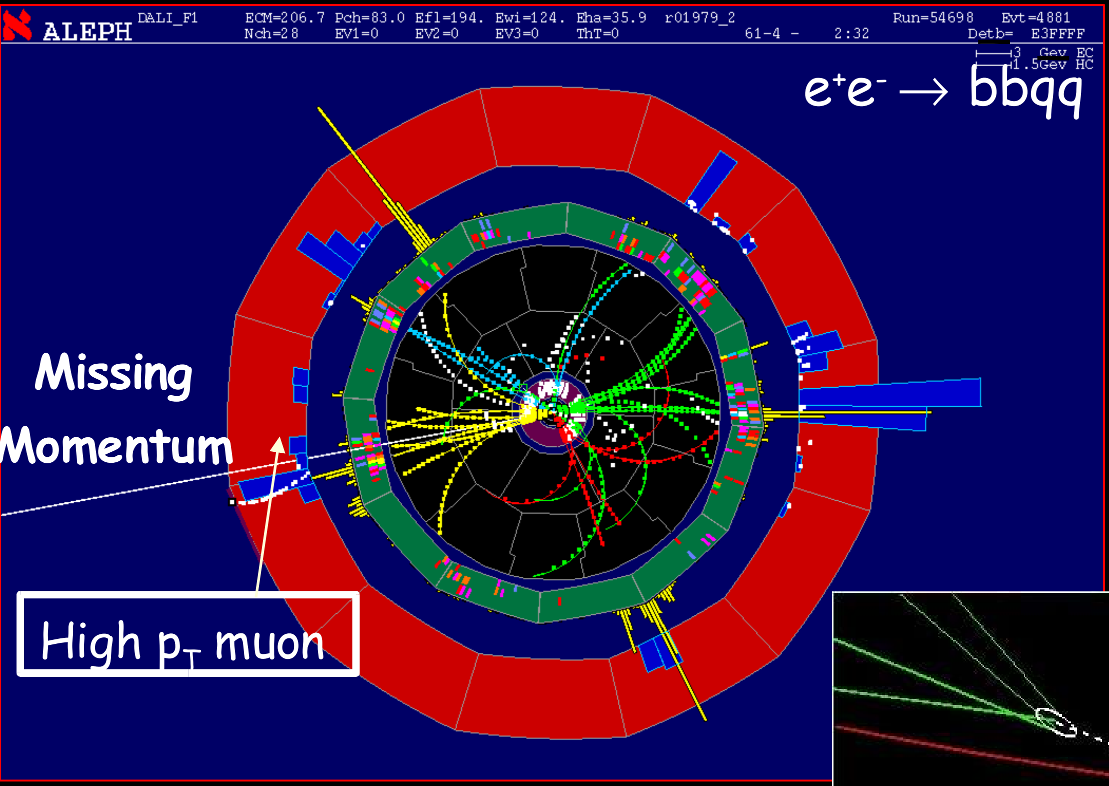
Summary of Higgs' model

- W mass agrees with Higgs theory
  - to 1 part in 1000
- Higgs mass should be:

$$96^{+60}_{-38}\,GeV$$

- We need to know whether it exists!

A wink from the Higgs?

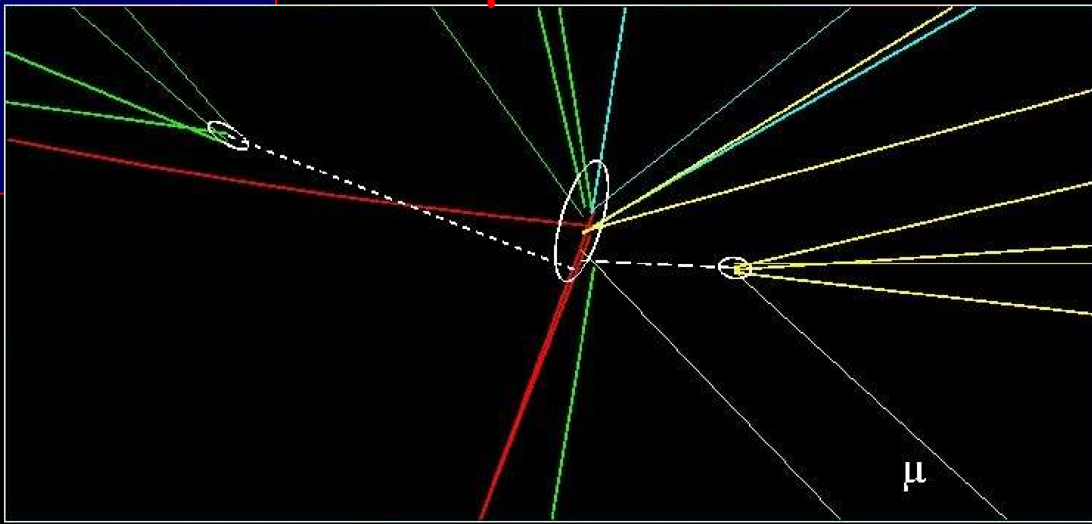


Serious Candidate

(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



b-tagging

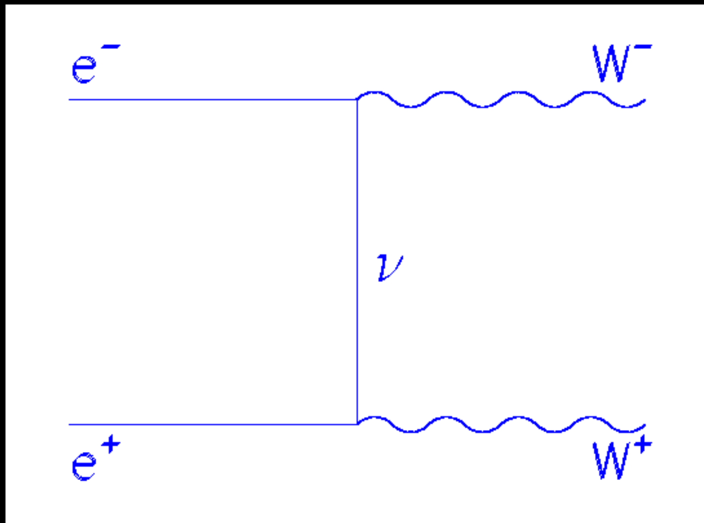
(0 = light quarks, 1 = b quarks)

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

The Search for the Higgs

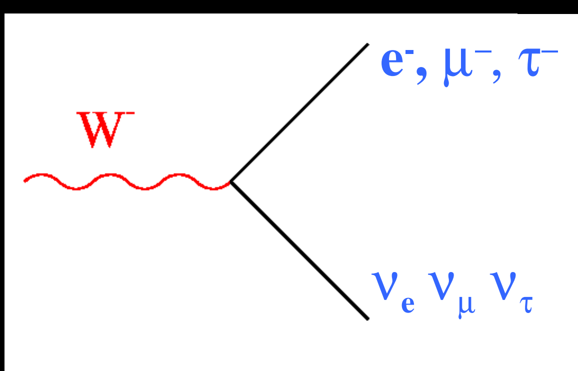
- In the late 1990s/2000 LEP at CERN ran with enough energy to make W pairs
- There was also hopes it might make a Higgs.

The W pairs:



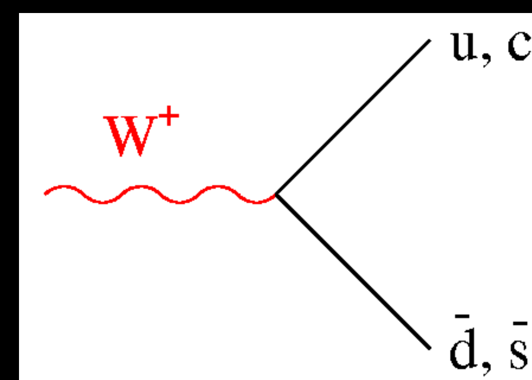
Ws produced by reactions like this one

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

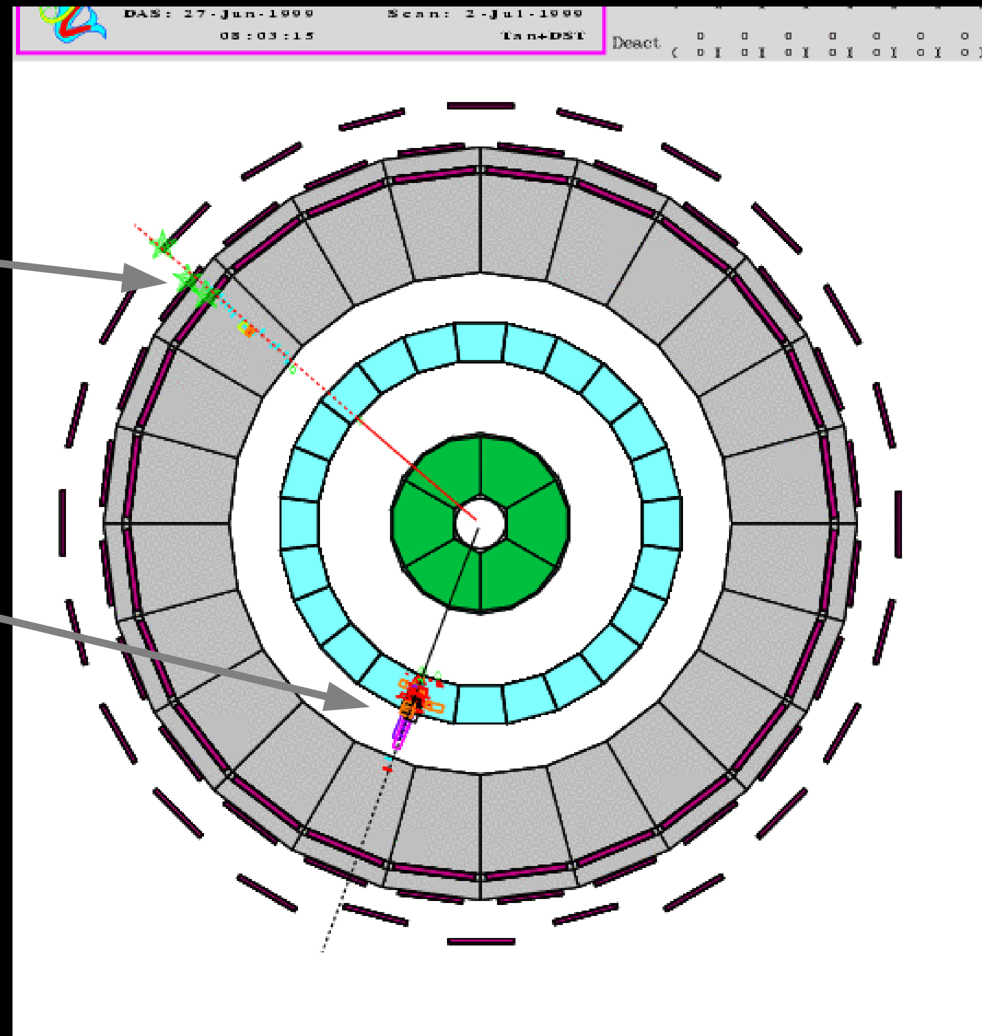


Into leptons (3 sorts)

Or quarks (2 sorts)

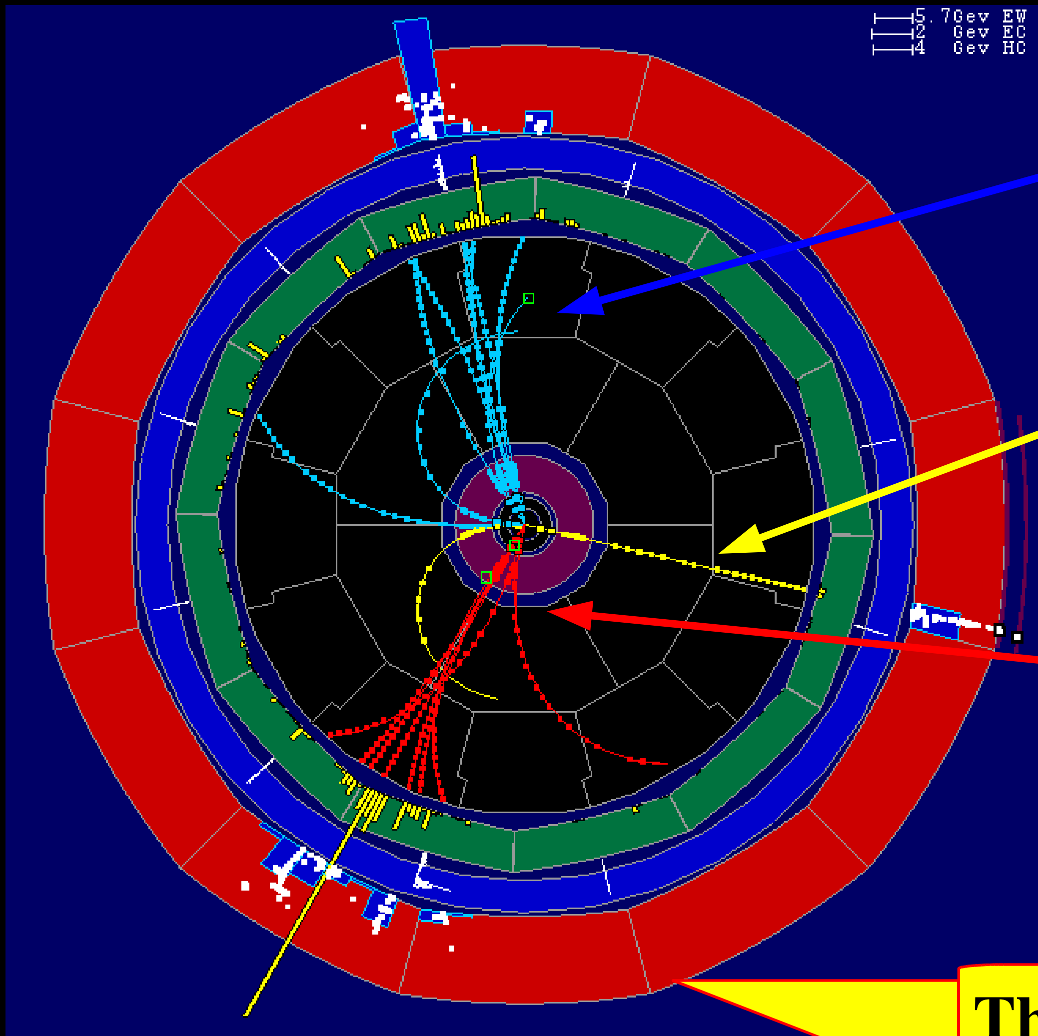


W^+W^-: What do we see?



Both Ws decayed to leptons

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



A jet from a quark

A muon

A jet from a quark

One W as 2 quarks, the other as a muon.

The nicest signature

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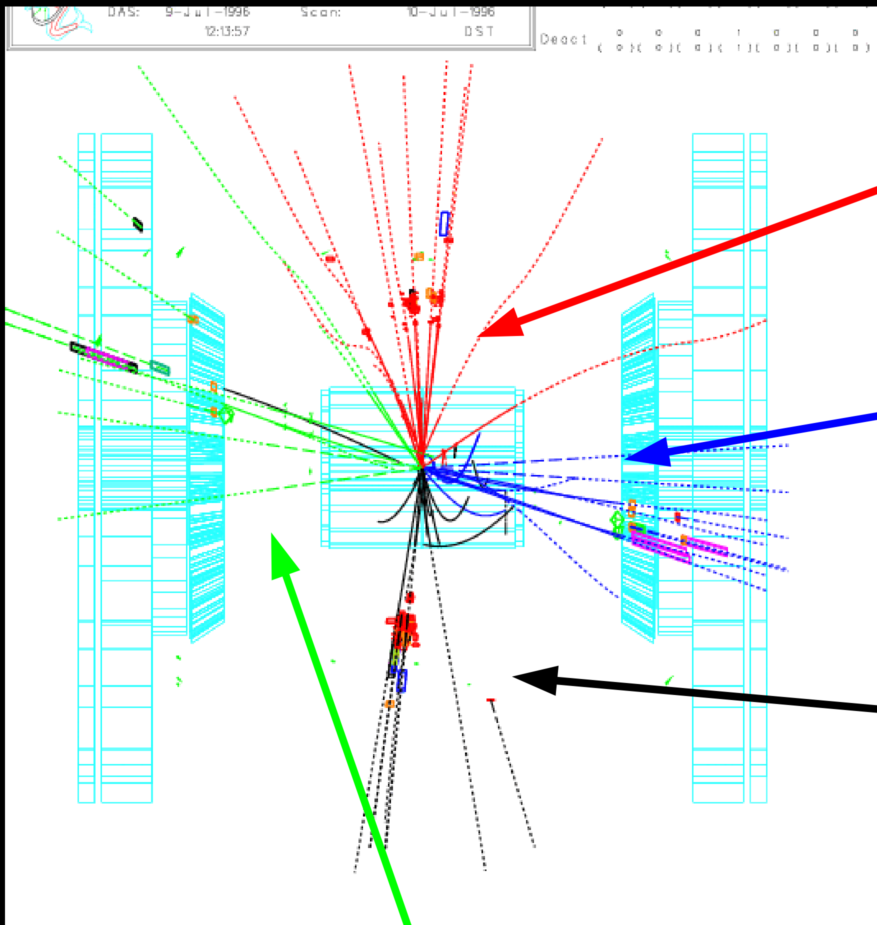
W^+W^-: What do we see?



A jet from a quark

A jet from a quark

A jet from a quark

A jet from a quark

Both Ws decayed to 2 quarks

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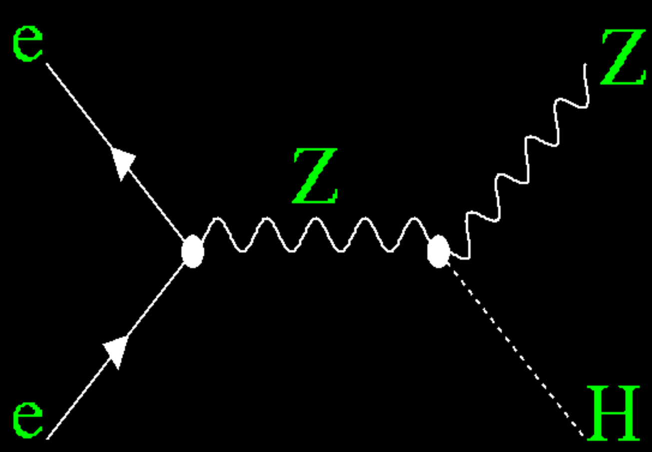
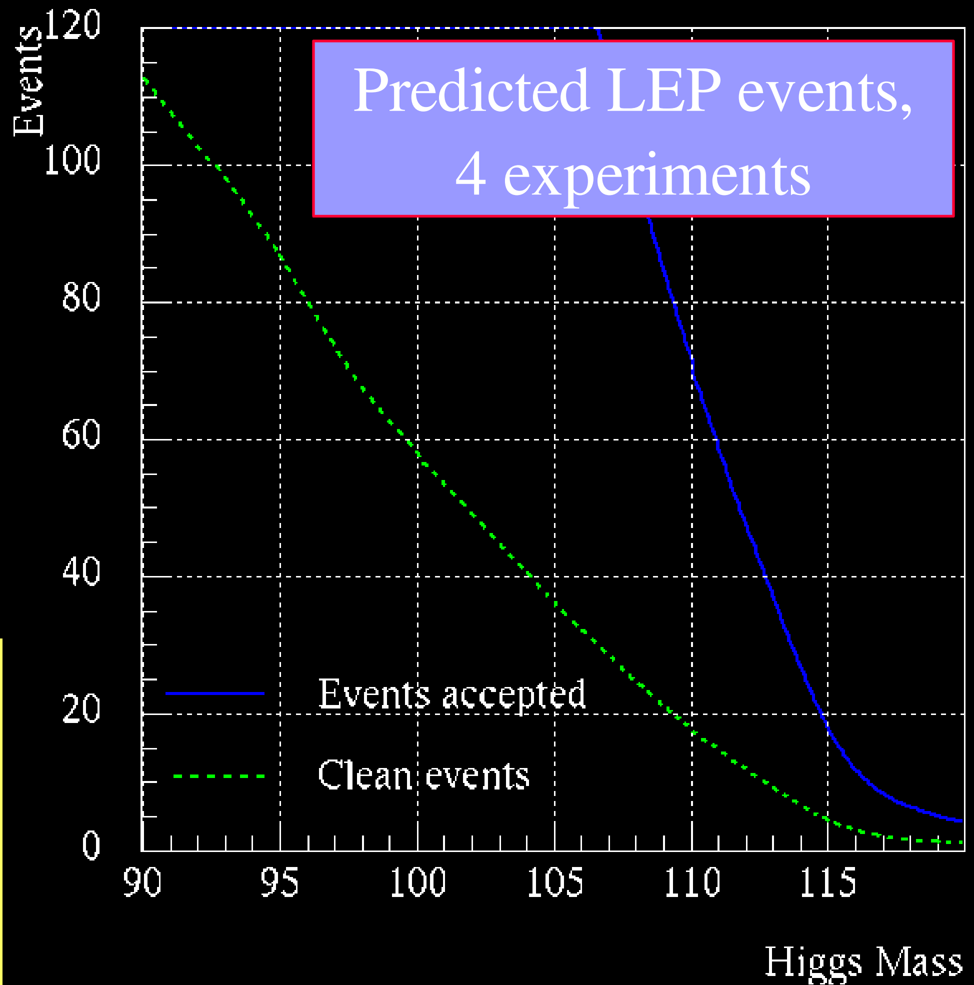
How might LEP make a Higgs ?





Make a Higgs and a Z together

So need Energy greater than Higgs mass plus Z mass

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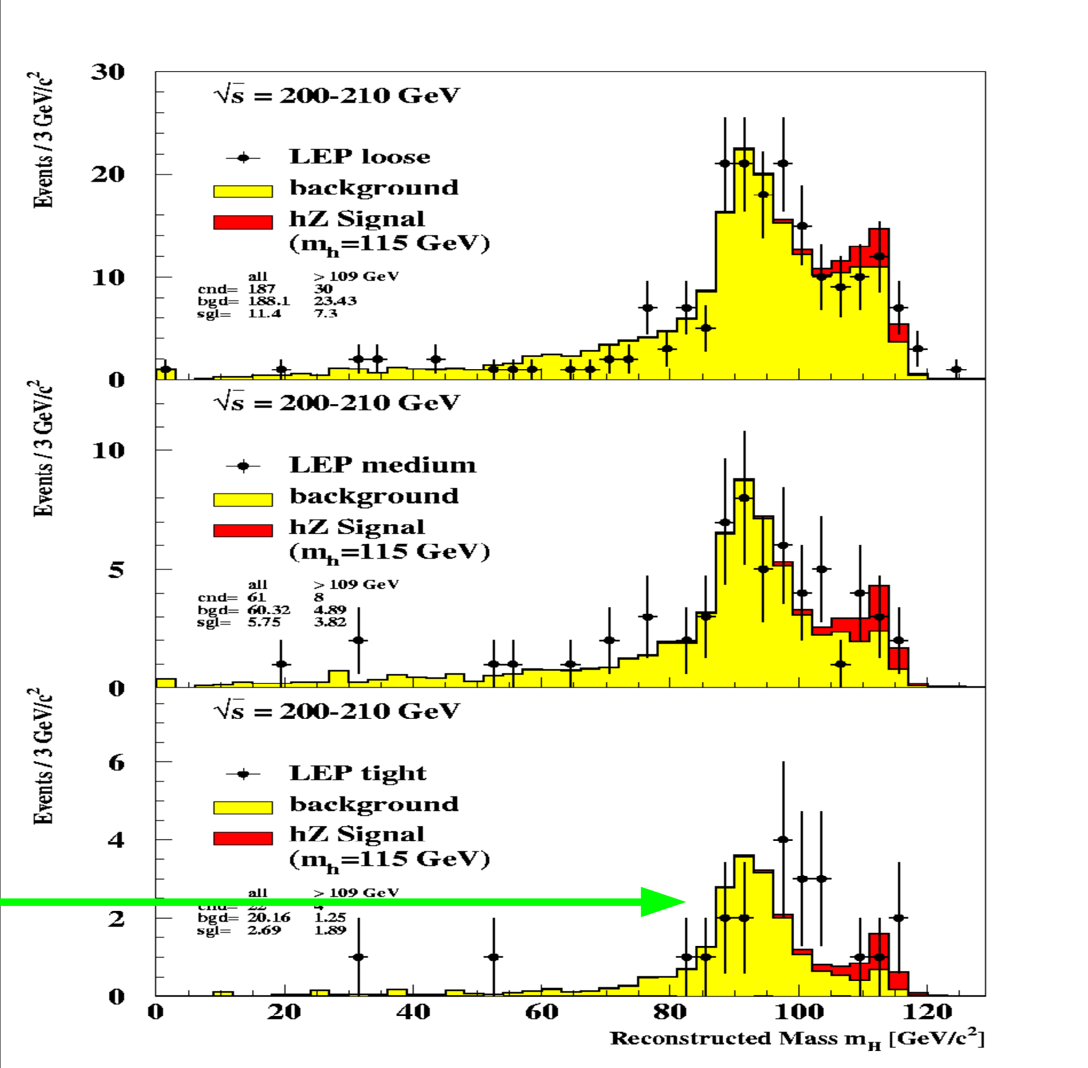
Was that the Higgs?

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



Yellow: background

Red: Predicted Higgs

Just one or two events...not enough to tell

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Some Unanswered Questions

- Does the Higgs exist? When will we know?
- Where is all the anti-matter?
- What about Gravity
  - Why do we get the cosmological constant wrong by 10^{120}?
- Why are there 3 generations of particles? And 3 colours?

Bruce Kennedy will answer all these after lunch!

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What are LEP and LHC?

	LEP	LHC
Beams of	Electrons	Protons
Energy, GeV	209	14,000
Max. Higgs Mass	115	~1000
Detailed?	Yes	No
Operation	1989-2000	2007-

plans started 1980's

Very different machines - using the same tunnel

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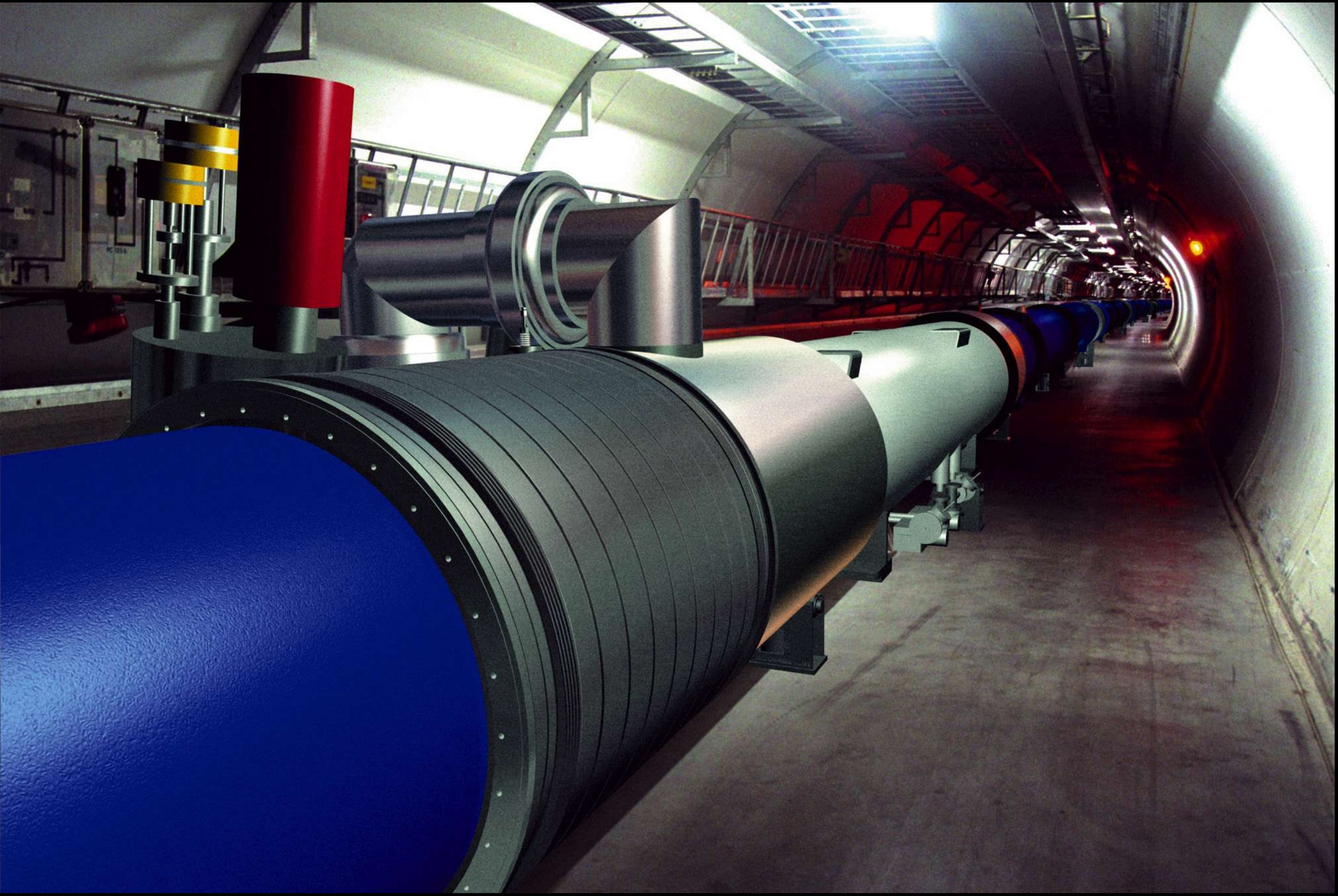
Now to be the LHC tunnel



27km of vacuum pipe

8.3Tesla bending magnets,

3^o above absolute zero

© Photo CERN

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Why big circular colliders?

Circular?

It allows us to re-use the particle: they have many chances to collide

They can be accelerated many times by the same device.

Magnetic fields guide beams round the ring in opposite directions

Big?

To reach high energy. Different limits for protons & electrons:

- **Protons: Limited by magnetic flux crossed. Need large BxL**
- **Electrons: They loose energy easily. Proportional to $(E/m)^4/r$**

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