Particle physics experiments

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International Particle Physics Outreach Group

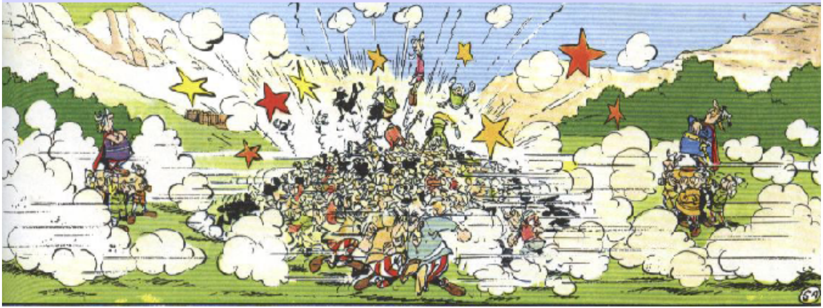
INTERNATIONAL MASTERCLASSES
hands on particle physics

Maynooth University
National University of Ireland Maynooth

Outline

1. Particles, mass and energy
2. The anatomy of a detector
3. Which particle is it?
4. Higgs hunting
5. Addendum: the origin of mass

Why?



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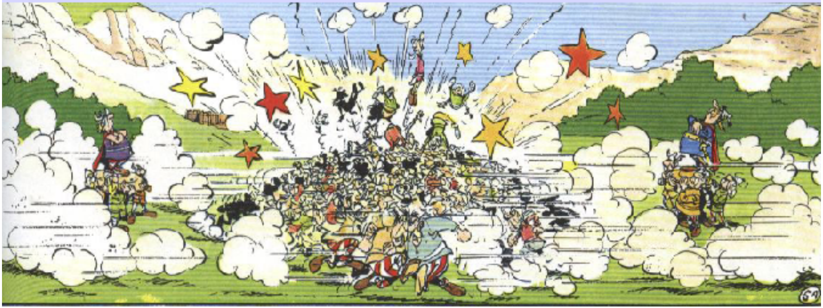
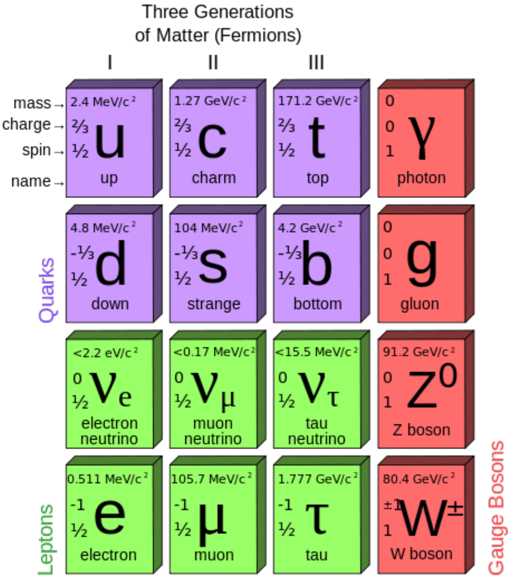


Einstein told us that mass is a form of energy, $E = mc^2$.
This means that if you have enough energy, you can create matter.

This is how physicists create lots and lots of particles in accelerators, when they bang particles together at enormous energies.

Meet the family



The strong force
acts only on quarks and gluons

The electromagnetic force
acts only on charged particles

The weak force
acts on everything!

The Higgs field
gives mass to the fundamental particles

Units of energy

Electronvolts

An electronvolt (eV) is the energy needed to move an electron across a voltage of 1 volt

It is equal to $1.60 \cdot 10^{-19}$J.

It requires about 13 eV to knock an electron out of a hydrogen atom

1 keV (kilo-electronvolt) = 1000 eV

1 MeV (mega-electronvolt) = 1 million eV

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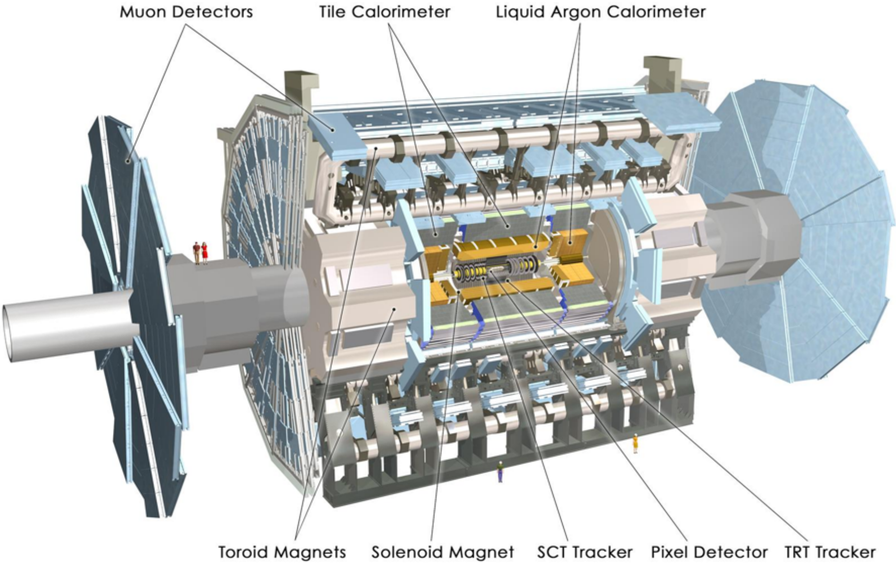
Since mass and energy are basically the same thing, particle physicists use the same units for both.

For example, we say that the mass of an electron is 0.511 MeV.

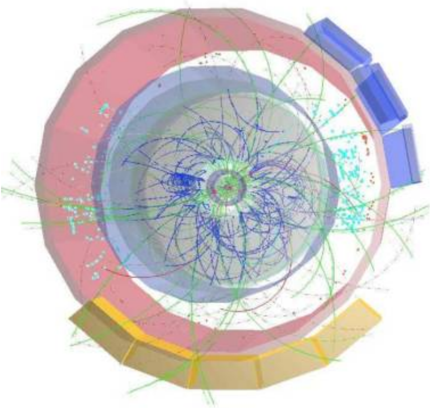
This really means 0.511 MeV/c^2.

The anatomy of a detector



The anatomy of a detector

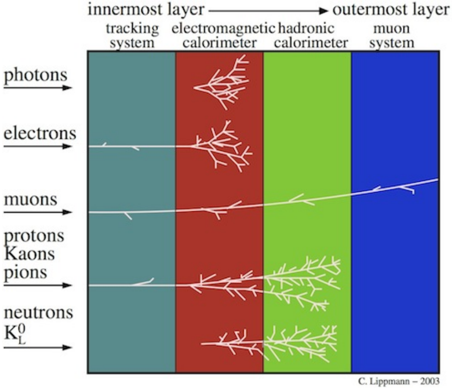
- Tracking system



As charged particles pass through gas or silicon strips, they ionise the matter around them and create currents. These are the tracks we observe.

The anatomy of a detector

- Tracking system
- Electromagnetic calorimeter
- Hadron calorimeter
  Beyond the tracking system are materials designed to stop all the particles and measure their energy



The anatomy of a detector

- Tracking system
- Electromagnetic calorimeter
- Hadron calorimeter
- Muon chambers
  Muons pass through the calorimeters almost unhindered, so we put detectors specifically designed to catch muons behind all the other components.
  They can give us crucial information about particles containing charm and beauty quarks.

Which particle is it?

To identify a particle, we need to find out

- its mass
- its charge
- whether it contains quarks
- whether it contains strange, charm or beauty quarks

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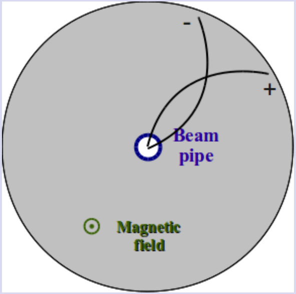
Charge

The tracking chambers have magnetic fields
The force on a particle in a magnetic field $\vec{B}$ is

$$\vec{F} = q(\vec{v} \times \vec{B}),$$

$$q = \text{charge}, \qquad \vec{v} = \text{velocity}$$



Mass

Energy and mass

Einstein told us that mass is a form of energy, $E = mc^2$.
There is another relation between energy and mass, $E^2 = (m_0 c^2)^2 + p^2 c^2$.

- p is the momentum $=$ mass $\times$ velocity
- m_0 is the rest mass — does not depend on speed of the particle
- All particles of the same type have the same rest mass

When particle physicists talk about mass, they always mean the rest mass!

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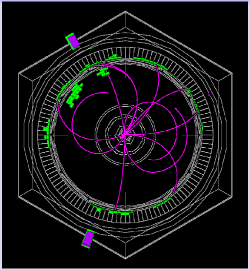
Measuring mass

The energy E is measured in the calorimeters

The momentum p is measured by the tracking system



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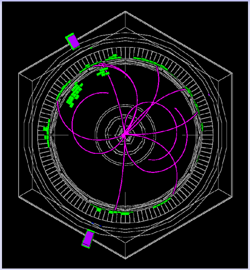

Put them together:

$$(mc^2)^2 = E^2 - (pc)^2$$

Invariant mass

What if a particle decays into two (or more) particles before we can register its energy and momentum?

$$X \to Y + Z$$

Energy conservation	$E_X = E_Y + E_Z$
Momentum conservation	$\vec{p_X} = \vec{p_Y} + \vec{p_Z}$
Relativity	$m_X^2 = E_X^2 - p_X^2$

Putting this together, we get

$$m_X^2 = (E_Y + E_Z)^2 - (\vec{p_Y} + \vec{p_Z})^2 = \text{the invariant mass!}$$

This way we can identify a particle even if we cannot "see" it!

Higgs hunting

The Higgs boson lives for only $10^{-22}s$
(and the Z boson even shorter)
That means it travels at most 1 fm (10^{-15}m) before decaying

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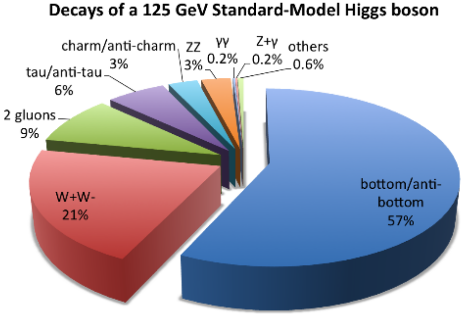
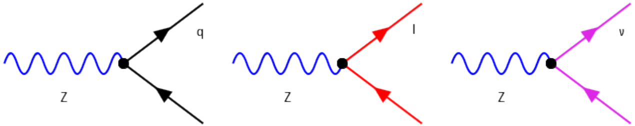
All we can see are the decay products



How do we identify the Higgs boson?

Z and Higgs interactions

Z decays



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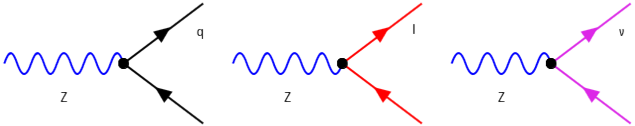

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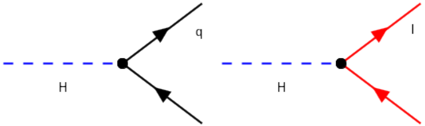
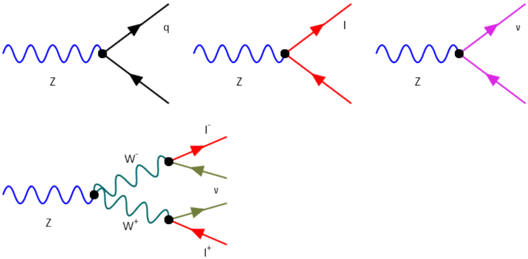


Spot the difference!

Z and Higgs interactions

Z decays



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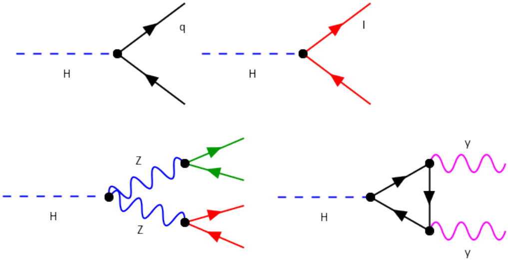

Signal and background

- There are many ways to make two photons, or two dileptons
- Some of them can even give the same invariant mass as Higgs or Z!
- All this other stuff we are not interested in is called background
- There is no way to tell if any single event is signal or background

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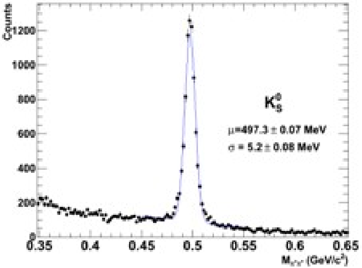
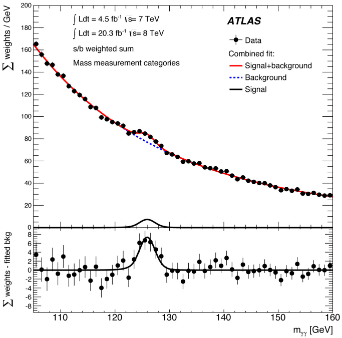
- We can only tell by counting lots of events and modelling the shape of signal and background





Is that all?

We have discovered all the (predicted) elements of the Standard Model, including the Z boson, the t quark and the Higgs boson.

You will be rediscovering the Z and the Higgs.

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Unanswered questions

- Why is there more matter than antimatter?
- What is the origin of neutrino masses?
- What is dark matter?
- What is dark energy?
- Why do particles have the masses they have?
- Is there quantum gravity?

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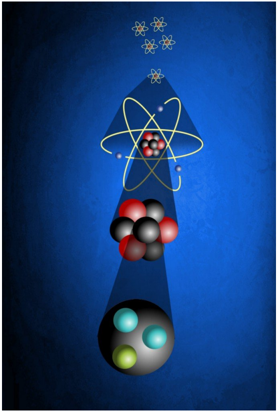
Maybe we will find new stuff at LHC: heavier Zs, gravitons, leptoquarks, surprises. . .

HAVE FUN!

Three Quarks for Muster Mark!



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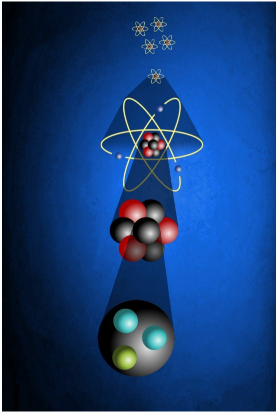

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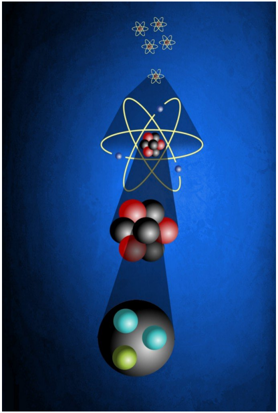


Quark Quark Quark!

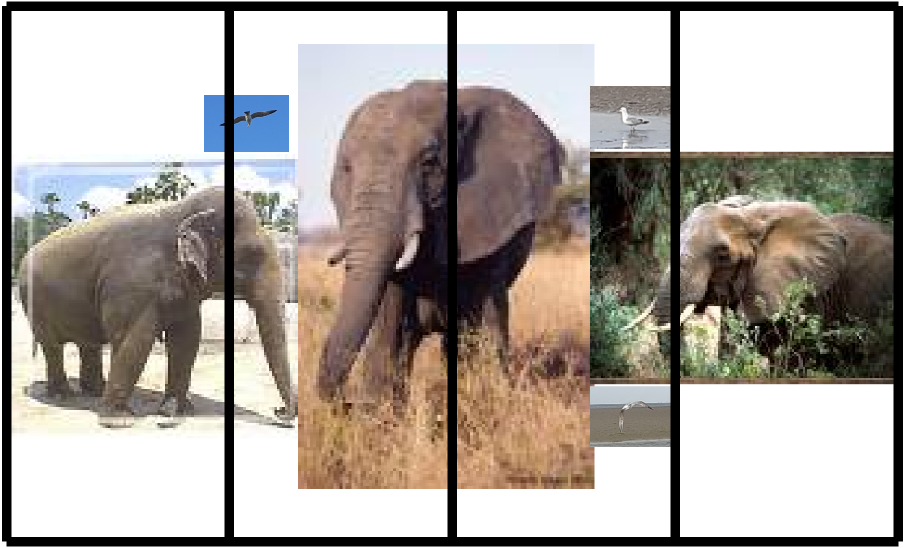
Let us say hello to the forces between quarks. . .

Strong interactions



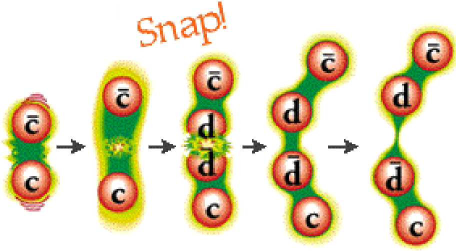



Strong interactions



Confinement

You cannot even theoretically chop a proton up into quarks!



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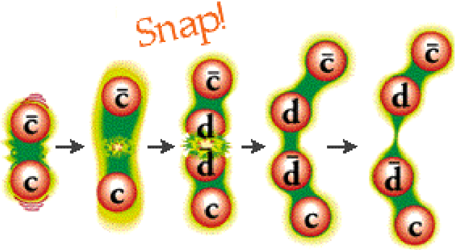

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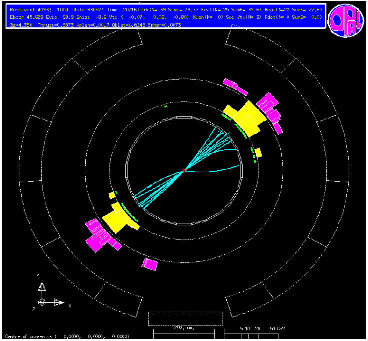

You will never see a single quark in a detector!

Instead you see jets: showers of hadrons

Quarks and hadrons

Quarks can only be found in colourless combinations = hadrons

They come in two types

Mesons

Quark + antiquark:

red +

antired

= black

$\pi^+ = u\overline{d}$, $K^0 = d\bar{s}$, $J/\psi = c\overline{c}$

Baryons

Three quarks:

red + green + blue = white

$p = uud, n = udd$
$\Lambda = uds, \Xi^0 = uss, \Omega^- = sss$

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The origin of mass

Quark masses:	$m_u \sim 2\text{MeV}$	$m_d \sim 5\text{MeV}$
Nucleon masses:	$m_p = 938.3\text{MeV}$	$m_n = 939.6\text{MeV}$

98% of the mass of everything around us comes from the strong force!