The world of quarks and leptons

Jon-Ivar Skullerud

Maynooth University

Particle Physics Masterclasses, Cairns, August 2024

International Particle Physics Outreach Group

INTERNATIONAL MASTERCLASSES
hands on particle physics

Maynooth University
National University of Ireland Maynooth

Outline

The big questions

(Some of them, at least. . .)

- What is the world made of?

The big questions

(Some of them, at least. . .)

- What is the world made of?
- What is the ultimate substance?
- What are the forces shaping this substance?
- How do things change?
- Why is there something rather than nothing?

Nature and the Greeks

$\Theta\alpha\lambda\tilde{\eta}\zeta$ $\dot{o}$ $M\iota\lambda\eta\sigma\iota o\zeta$ (624–546BC)

All is water!

Nature and the Greeks

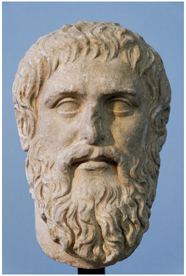
$\Theta\alpha\lambda\tilde{\eta}\zeta$ $\dot{o}$ $M\iota\lambda\eta\sigma\iota o\zeta$ (624–546BC)

All is water!

$A\nu\alpha\xi\iota\mu\alpha\nu\delta\rho o\zeta$ (610–546BC)

To $\alpha\pi\varepsilon\iota\rho o\nu$ (The unlimited)

The elements

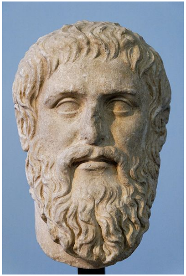


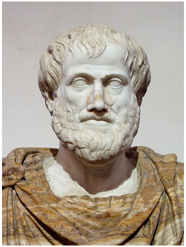
$\Pi\lambda\alpha\tau\omega\nu$ (427–347BC)

- The material world is a mirage
- Ultimate reality is ideas and mathematical forms!

5 regular solids $\rightarrow$ 5 elements

The elements





$\Pi\lambda\alpha\tau\omega\nu$ (427–347BC)

- The material world is a mirage
- Ultimate reality is ideas and mathematical forms!

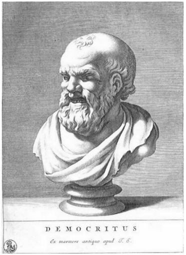
5 regular solids $\rightarrow$ 5 elements

$A\rho\iota\sigma\tau o\tau\varepsilon\lambda\eta\zeta$ (384–322BC)

Laws of motion for the elements

- Earth and water sink down
- Air and fire rise up
- The æther moves in perfect circles

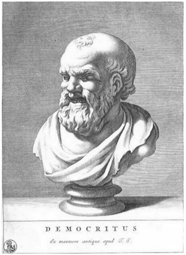
Atomism



$\Delta\eta\mu o\kappa\rho\iota\tau o\zeta$ (460–370BC)

What happens if you chop stuff up more and more?

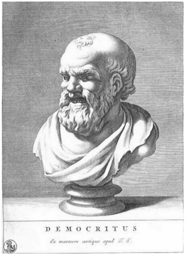
Atomism



$\Delta\eta\mu o\kappa\rho\iota\tau o\zeta$ (460–370BC)

What happens if you chop stuff up more and more?
$\alpha\tau o\mu o\zeta$ = uncuttable

Atomism



$\Delta\eta\mu o\kappa\rho\iota\tau o\zeta$ (460–370BC)

What happens if you chop stuff up more and more?
$\alpha\tau o\mu o\zeta$ = uncuttable

Naïve atomism

All is atoms and void!

- Atoms are in continuous motion
- They have different shapes, hooks etc $\rightarrow$ can stick together
- Soul atoms are smoother, lighter than the rest!
- We cannot sense the atoms

May the Force be with you

What do you feel when you bang your hand against the table?

- not atoms or nuclei or electrons

May the Force be with you

What do you feel when you bang your hand against the table?

- not atoms or nuclei or electrons
- but forces between them

May the Force be with you

What do you feel when you bang your hand against the table?

- not atoms or nuclei or electrons
- but forces between them
- and forces between them and your hand!

May the Force be with you

What do you feel when you bang your hand against the table?

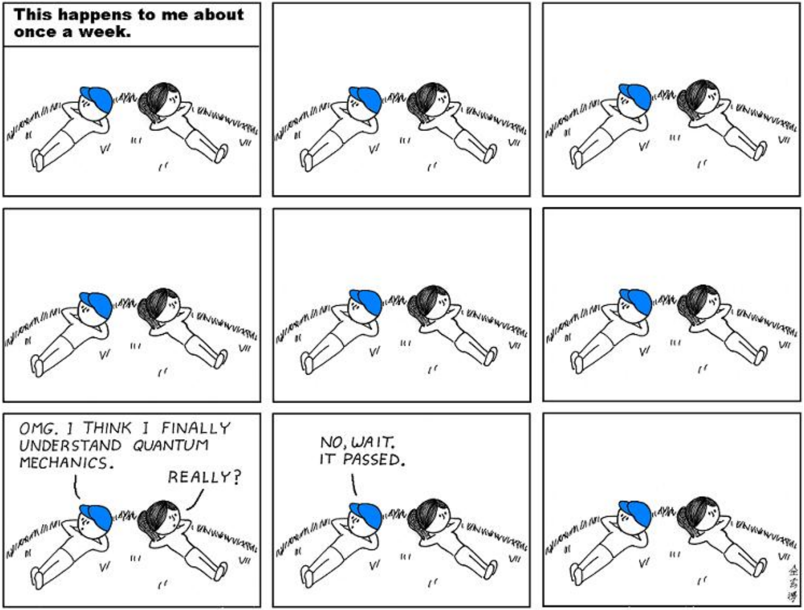
- not atoms or nuclei or electrons
- but forces between them
- and forces between them and your hand!

Force fields

All matter is surrounded by and influenced by a force field

Is this the ultimate reality?

The mysterious quantum world



The quantum world

Relativistic quantum theory tells us many strange things:

- Matter and forces are the same kind of stuff

The quantum world

Relativistic quantum theory tells us many strange things:

- Matter and forces are the same kind of stuff
- Both are described as both particles and fields

The quantum world

Relativistic quantum theory tells us many strange things:

- Matter and forces are the same kind of stuff
- Both are described as both particles and fields
- Quantum particles are everywhere and nowhere: the fundamental particles have no size, but can be anywhere or everywhere in space

The quantum world

Relativistic quantum theory tells us many strange things:

- Matter and forces are the same kind of stuff
- Both are described as both particles and fields
- Quantum particles are everywhere and nowhere: the fundamental particles have no size, but can be anywhere or everywhere in space
- The subatomic world is indeterminate

The quantum world

Relativistic quantum theory tells us many strange things:

- Matter and forces are the same kind of stuff
- Both are described as both particles and fields
- Quantum particles are everywhere and nowhere: the fundamental particles have no size, but can be anywhere or everywhere in space
- The subatomic world is indeterminate
- Since energy and mass are the same, matter can be made out of pure energy, and vice-versa!

The quantum world

Relativistic quantum theory tells us many strange things:

- Matter and forces are the same kind of stuff
- Both are described as both particles and fields
- Quantum particles are everywhere and nowhere: the fundamental particles have no size, but can be anywhere or everywhere in space
- The subatomic world is indeterminate
- Since energy and mass are the same, matter can be made out of pure energy, and vice-versa!
- Energy comes in bunches called particles

The quantum world

Relativistic quantum theory tells us many strange things:

- Matter and forces are the same kind of stuff
- Both are described as both particles and fields
- Quantum particles are everywhere and nowhere: the fundamental particles have no size, but can be anywhere or everywhere in space
- The subatomic world is indeterminate
- Since energy and mass are the same, matter can be made out of pure energy, and vice-versa!
- Energy comes in bunches called particles
- The number of particles is not conserved!

The quantum world

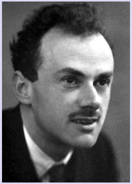
Relativistic quantum theory tells us many strange things:

- Matter and forces are the same kind of stuff
- Both are described as both particles and fields
- Quantum particles are everywhere and nowhere: the fundamental particles have no size, but can be anywhere or everywhere in space
- The subatomic world is indeterminate
- Since energy and mass are the same, matter can be made out of pure energy, and vice-versa!
- Energy comes in bunches called particles
- The number of particles is not conserved!
- You can ‘borrow’ energy, for example to make particles, as long as you give it back fast enough!

Two types of stuff

Fermions

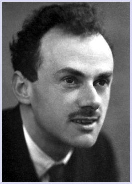
- cannot be at the same place at the same time
- can [usually] only be created in pairs
- have half-integer spin
- most (all?) fundamental matter particles are fermions



Two types of stuff

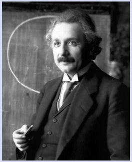
Fermions

- cannot be at the same place at the same time
- can [usually] only be created in pairs
- have half-integer spin
- most (all?) fundamental matter particles are fermions



Bosons

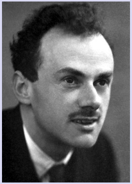
- can be piled up on top of each other
- may be created and destroyed at will
- have integer spin
- all fundamental force particles are bosons



Two types of stuff

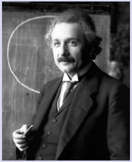
Fermions

- cannot be at the same place at the same time
- can [usually] only be created in pairs
- have half-integer spin
- most (all?) fundamental matter particles are fermions



Bosons

- can be piled up on top of each other
- may be created and destroyed at will
- have integer spin
- all fundamental force particles are bosons



Something consisting of an even number of fermions is a boson
Something consisting of an odd number of fermions is a fermion

Energy and matter

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.

Energy and matter

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.

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, which does not depend on how fast the particle is moving
- All particles of the same type have the same rest mass

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

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

1 GeV (giga-electronvolt) = 1 billion eV

1 TeV (tera-electronvolt) = 1 trillion eV

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
1 GeV (giga-electronvolt) = 1 billion eV
1 TeV (tera-electronvolt) = 1 trillion eV

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$/c^2$.

Energy and size

In quantum mechanics, any particle has a wavelength, which is inversely proportional to its momentum
The larger the momentum (and energy), the smaller the wavelength!

The wavelength determines how small structures the particle can 'see':
The smaller the wavelength, the smaller the structure we can see, or

The larger the energy, the smaller 'things' we can see

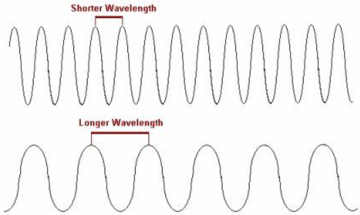
Energy and size

In quantum mechanics, any particle has a wavelength, which is inversely proportional to its momentum
The larger the momentum (and energy), the smaller the wavelength!

The wavelength determines how small structures the particle can 'see':
The smaller the wavelength, the smaller the structure we can see, or

The larger the energy, the smaller 'things' we can see

The LHC is a giant microscope!



The standard model: ordinary matter

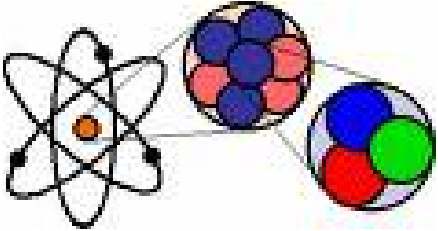
Nearly everything we see around us can be described by

3 matter particles

- up quark u
- down quark d
- electron e^-

2 forces

- electromagnetism (photon γ)
- strong force (gluons g)



Radioactivity

Beta decay $n \rightarrow p^+ + e^-$

- Does not fit with the strong or electromagnetic force
- Need a new force — weak force (W bosons)
- Crucial for stability of nuclei, processes in the sun
- n, p, e are all fermions: spin/statistics rules broken?
- Energy not conserved?

Radioactivity

Beta decay $n \to p^+ + e^-$

- Does not fit with the strong or electromagnetic force
- Need a new force — weak force (W bosons)
- Crucial for stability of nuclei, processes in the sun
- n, p, e are all fermions: spin/statistics rules broken?
- Energy not conserved?

Dear radioactive ladies and gentlemen

As the bearer of these lines . . . will explain more exactly, considering the 'false' statistics of N-14 and Li-6 nuclei, as well as the continuous β-spectrum, I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the energy theorem. Namely [there is] the possibility that there could exist in the nuclei electrically neutral particles that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle, . . .

Neutrinos

How do we see neutrinos?

Neutrinos

How do we see neutrinos?

Usually we don't!

We see that there is missing energy.

Only neutrinos could have run away with the energy:

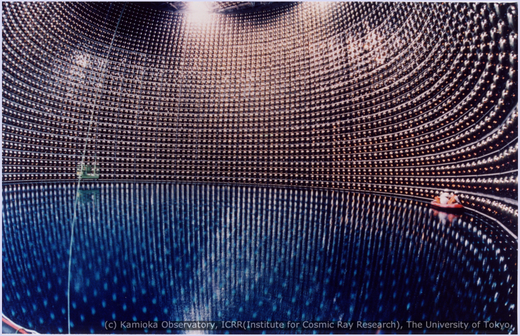
all other particles are caught by the detector!

Neutrinos

How do we see neutrinos?

Usually we don't!
We see that there is missing energy.
Only neutrinos could have run away with the energy:
all other particles are caught by the detector!

Or we fill a huge tank
with water or soap...



Meet the rest of the family

Who ordered that?

Meet the rest of the family

Who ordered that?

The muon was discovered in 1935.

Meet the rest of the family

Who ordered that?

The muon was discovered in 1935.

The muon is an overweight cousin of the electron:

$m_e = 0.511\text{MeV}$, $m_\mu = 105.7\text{MeV}$.

It keeps itself with its own neutrino, ν_μ

Meet the rest of the family

Who ordered that?

The muon was discovered in 1935.

The muon is an overweight cousin of the electron:

$m_e = 0.511\text{MeV}$, $m_\mu = 105.7\text{MeV}$.

It keeps itself with its own neutrino, ν_μ

Something strange

Some particles (K mesons and hyperons), discovered in the 1940s, behaved in a strange way, so strangeness was introduced to explain this.

We now know these particles contain a strange quark (s)

Meet the rest of the family

Who ordered that?

The muon was discovered in 1935.

The muon is an overweight cousin of the electron:

$m_e = 0.511\text{MeV}$, $m_\mu = 105.7\text{MeV}$.

It keeps itself with its own neutrino, ν_μ

Something strange

Some particles (K mesons and hyperons), discovered in the 1940s, behaved in a strange way, so strangeness was introduced to explain this.

We now know these particles contain a strange quark (s)

The strange quark needs a partner, the charm quark (c, discovered 1974).

Meet the rest of the family

Who ordered that?

The muon was discovered in 1935.

The muon is an overweight cousin of the electron:

$m_e = 0.511\text{MeV}$, $m_\mu = 105.7\text{MeV}$.

It keeps itself with its own neutrino, ν_μ

Something strange

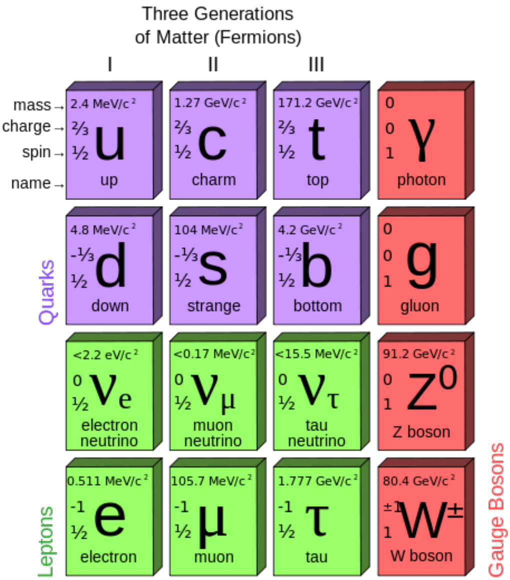
Some particles (K mesons and hyperons), discovered in the 1940s, behaved in a strange way, so strangeness was introduced to explain this. We now know these particles contain a strange quark (s)

The strange quark needs a partner, the charm quark (c, discovered 1974).

From the 1970s on, a third, obese set of cousins was discovered:

- the tau lepton (τ)
- its neutrino (ν_τ)
- the beauty / bottom quark (b)
- its partner, truth / top (t)

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!

More about the weak force

The weak force can transform a quark or lepton into its partner:

$$\mu^- \rightarrow \nu_\mu + W^- \rightarrow \nu_\mu + e^- + \overline{\nu}_e$$
$$u \rightarrow d + W^+ \rightarrow d + \mu^+ + \nu_\mu$$

More about the weak force

The weak force can transform a quark or lepton into its partner:

$$\mu^- \to \nu_\mu + W^- \to \nu_\mu + e^- + \overline{\nu}_e$$
$$u \to d + W^+ \to d + \mu^+ + \nu_\mu$$

But the weak force can also change a quark into its cousin:

$$s \to u + W^- \to u + \overline{u} + s$$

This is because the W has got the quarks all mixed up!

More about the weak force

The weak force can transform a quark or lepton into its partner:

$$\mu^- \rightarrow \nu_\mu + W^- \rightarrow \nu_\mu + e^- + \overline{\nu}_e$$
$$u \rightarrow d + W^+ \rightarrow d + \mu^+ + \nu_\mu$$

But the weak force can also change a quark into its cousin:

$$s \rightarrow u + W^- \rightarrow u + \overline{u} + s$$

This is because the W has got the quarks all mixed up!

Strange decays

$$K^0 \rightarrow \pi^- + \pi^+$$
$$\Lambda \rightarrow p + \pi^-$$
$$\overline{\Lambda} \rightarrow \overline{p} + \pi^+$$
$$\Xi^- \rightarrow \Lambda + \pi^- \rightarrow p + \pi^+ + \pi^-$$

More about the weak force

The weak force can transform a quark or lepton into its partner:

$$\mu^- \to \nu_\mu + W^- \to \nu_\mu + e^- + \overline{\nu}_e$$
$$u \to d + W^+ \to d + \mu^+ + \nu_\mu$$

But the weak force can also change a quark into its cousin:

$$s \to u + W^- \to u + \overline{u} + s$$

This is because the W has got the quarks all mixed up!

Strange decays

$$K^0 \to \pi^- + \pi^+ \qquad d\overline{s} \to d\overline{u} + u\overline{d}$$
$$\Lambda \to p + \pi^- \qquad uds \to uud + d\overline{u}$$
$$\overline{\Lambda} \to \overline{p} + \pi^+ \qquad \overline{uds} \to \overline{uud} + u\overline{d}$$
$$\Xi^- \to \Lambda + \pi^- \to p + \pi^+ + \pi^- \qquad dss \to uds + d\overline{u}$$

More about the weak force

The weak force can transform a quark or lepton into its partner:

$$\mu^- \to \nu_\mu + W^- \to \nu_\mu + e^- + \overline{\nu}_e$$
$$u \to d + W^+ \to d + \mu^+ + \nu_\mu$$

But the weak force can also change a quark into its cousin:

$$s \to u + W^- \to u + \overline{u} + s$$

This is because the W has got the quarks all mixed up!

The Z-boson is neutral, like a heavy photon
but also couples to neutrinos:

$$\mu^+ + \mu^- \to Z \to \nu_e + \overline{\nu}_e$$

More about the weak force

The weak force can transform a quark or lepton into its partner:

$$\mu^- \to \nu_\mu + W^- \to \nu_\mu + e^- + \overline{\nu}_e$$
$$u \to d + W^+ \to d + \mu^+ + \nu_\mu$$

But the weak force can also change a quark into its cousin:

$$s \to u + W^- \to u + \overline{u} + s$$

This is because the W has got the quarks all mixed up!

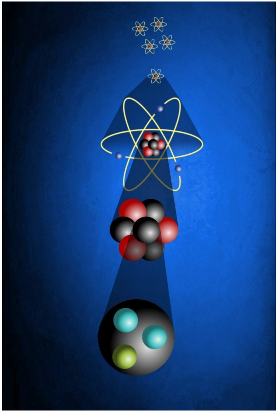
The Z-boson is neutral, like a heavy photon
but also couples to neutrinos:

$$\mu^+ + \mu^- \to Z \to \nu_e + \overline{\nu}_e$$

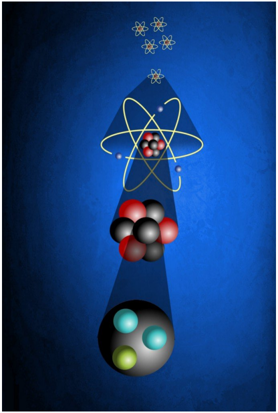
The W and Z bosons also interact with themselves:

$$W^+ + W^- \to Z + Z$$

Three Quarks for Muster Mark!

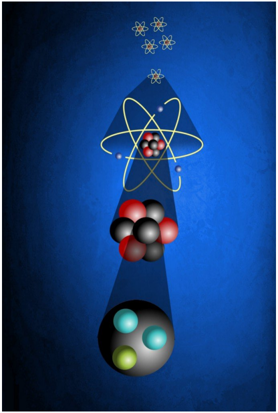


Three Quarks for Muster Mark!



Quark Quark Quark!

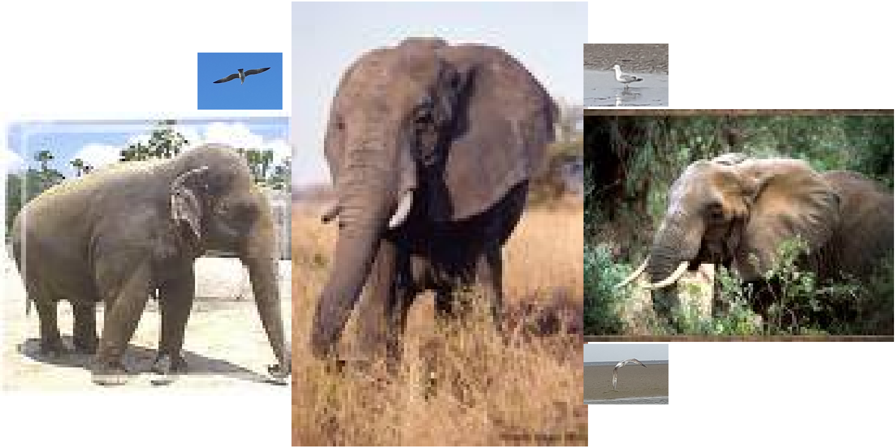
Three Quarks for Muster Mark!



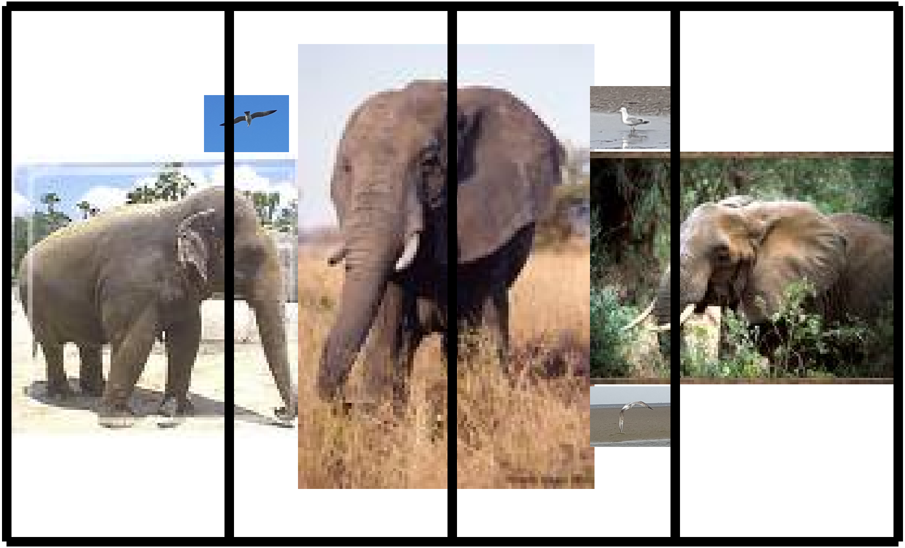
Quark Quark Quark!

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

Strong interactions

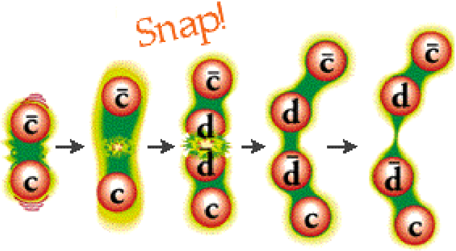


Strong interactions



Confinement

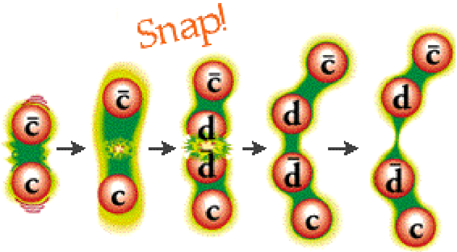
You cannot even theoretically chop a proton up into quarks!



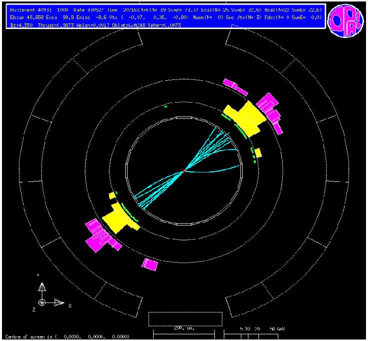
As the quarks are pulled apart, more and more energy is needed until a quark–antiquark pair pops out!

Confinement

You cannot even theoretically chop a proton up into quarks!



As the quarks are pulled apart, more and more energy is needed until a quark–antiquark pair pops out!



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

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

Baryons

Three quarks:

red + green + blue = white

$p = uud, n = udd, \Omega^- = sss$

Quarks and hadrons

Quarks can only be found in colourless combinations = hadrons

They come in two types

Mesons

Quark + antiquark:

red +

antired

= black

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

Baryons

Three quarks:

red + green + blue = white

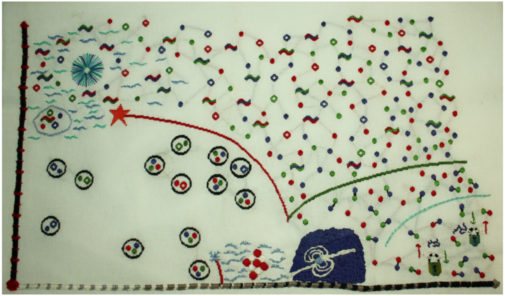
$p = uud, n = udd, \Omega^- = sss$

The origin of mass

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

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

Quark–gluon plasma



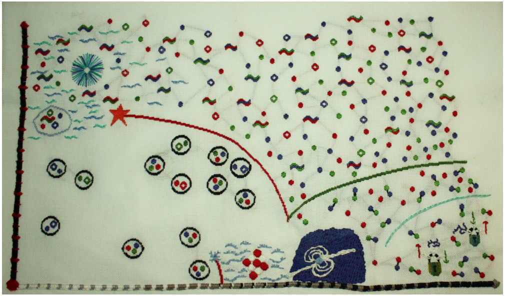
At temperatures of 160 MeV (nearly 2 trillion Kelvin) quarks are deconfined

It has not been that hot since the Big Bang!

LHC is creating these temperatures

$\longrightarrow$ the Little Bang

Quark–gluon plasma



At temperatures of 160 MeV (nearly 2 trillion Kelvin) quarks are deconfined

It has not been that hot since the Big Bang!

LHC is creating these temperatures

$\longrightarrow$ the Little Bang

How do we know we have made a quark–gluon plasma?

- Jet quenching?
- Dilepton enhancement?
- J/ψ suppression?
- Strangeness enhancement

The origin of [the rest of the] mass

If W bosons were like photons and gluons, they would have no mass
We know this is not true!

The origin of [the rest of the] mass

If W bosons were like photons and gluons, they would have no mass
We know this is not true!

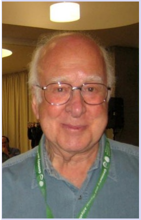
Also, the theory only works if quarks and leptons have no mass
We know this is not true!

The origin of [the rest of the] mass

If W bosons were like photons and gluons, they would have no mass
We know this is not true!

Also, the theory only works if quarks and leptons have no mass
We know this is not true!

The (elusive) Higgs



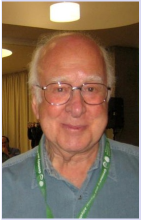
The Higgs field acts as a syrup that makes everything heavy

The origin of [the rest of the] mass

If W bosons were like photons and gluons, they would have no mass
We know this is not true!

Also, the theory only works if quarks and leptons have no mass
We know this is not true!

The (elusive) Higgs



The Higgs field acts as a syrup that makes everything heavy

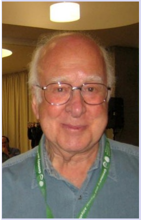
- The Higgs interacts with everything
  (but preferably with heavier stuff, like t, Z, W or b)
- It is neither matter nor force
- The Higgs boson is an excitation of the Higgs field

The origin of [the rest of the] mass

If W bosons were like photons and gluons, they would have no mass
We know this is not true!

Also, the theory only works if quarks and leptons have no mass
We know this is not true!

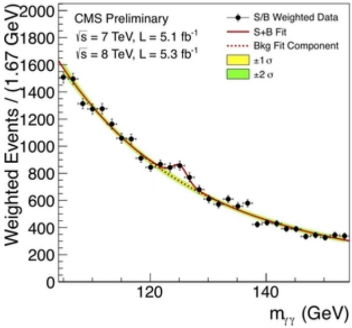
The (elusive) Higgs

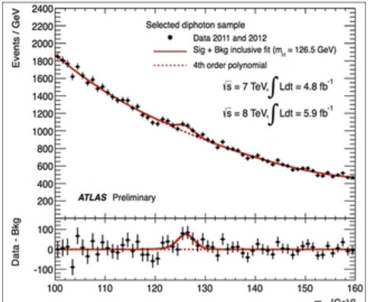


The Higgs field acts as a syrup that makes everything heavy

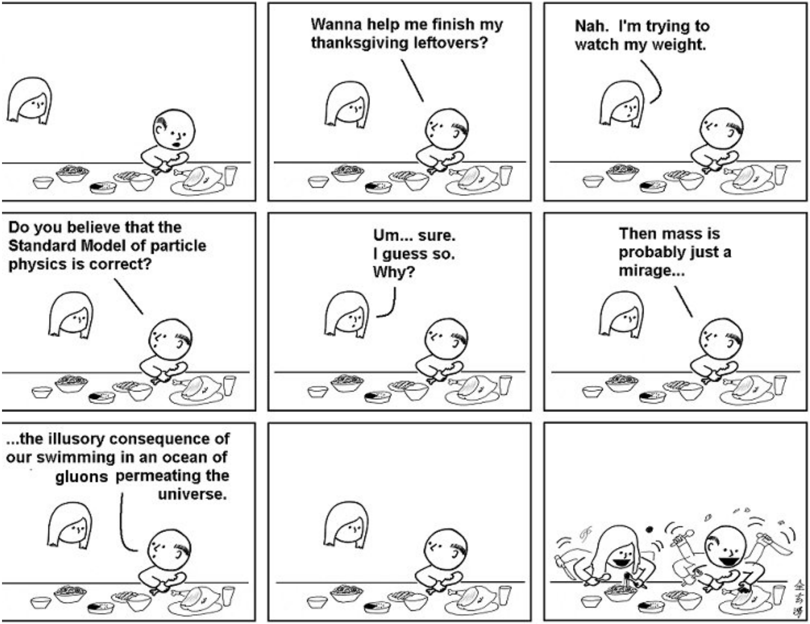
- The Higgs interacts with everything
  (but preferably with heavier stuff, like t, Z, W or b)
- It is neither matter nor force
- The Higgs boson is an excitation of the Higgs field
- It had never been seen (until 2012)

Discovery of the Higgs boson





- On 4 July 2012 the ATLAS and CMS collaborations announced the discovery of a boson with a mass of 125 GeV.
- Like looking for a needle in a hay stack? Wrong, it is like looking for hay in a hay stack: find the excess of hay of some given length (Sean Carroll)


Wanna help me finish my thanksgiving leftovers?
Nah. I'm trying to watch my weight.
Do you believe that the Standard Model of particle physics is correct?
Um... sure. I guess so. Why?
Then mass is probably just a mirage...
...the illusory consequence of our swimming in an ocean of gluons permeating the universe.

Open questions

- Is the Higgs boson really an elementary particle?

Open questions

- Is the Higgs boson really an elementary particle?
- How exactly are quarks and gluons confined?

Open questions

- Is the Higgs boson really an elementary particle?
- How exactly are quarks and gluons confined?
- Why is there something rather than nothing?

Open questions

- Is the Higgs boson really an elementary particle?
- How exactly are quarks and gluons confined?
- Why is there something rather than nothing?
- Why three generations? And why just those masses?

Open questions

- Is the Higgs boson really an elementary particle?
- How exactly are quarks and gluons confined?
- Why is there something rather than nothing?
- Why three generations? And why just those masses?
- How do neutrinos get their masses?

Open questions

- Is the Higgs boson really an elementary particle?
- How exactly are quarks and gluons confined?
- Why is there something rather than nothing?
- Why three generations? And why just those masses?
- How do neutrinos get their masses?
- Why is there something rather than nothing?
  (more matter than antimatter)

Open questions

- Is the Higgs boson really an elementary particle?
- How exactly are quarks and gluons confined?
- Why is there something rather than nothing?
- Why three generations? And why just those masses?
- How do neutrinos get their masses?
- Why is there something rather than nothing?
  (more matter than antimatter)
- What is dark matter?

Open questions

- Is the Higgs boson really an elementary particle?
- How exactly are quarks and gluons confined?
- Why is there something rather than nothing?
- Why three generations? And why just those masses?
- How do neutrinos get their masses?
- Why is there something rather than nothing?
  (more matter than antimatter)
- What is dark matter?
- What the $%!=* is dark energy?
  (or why did particle physics get it so horribly wrong?)

Open questions

- Is the Higgs boson really an elementary particle?
- How exactly are quarks and gluons confined?
- Why is there something rather than nothing?
- Why three generations? And why just those masses?
- How do neutrinos get their masses?
- Why is there something rather than nothing?
  (more matter than antimatter)
- What is dark matter?
- What the $%!=* is dark energy?
  (or why did particle physics get it so horribly wrong?)
- Can we find a theory of quantum gravity?

Open questions

- Is the Higgs boson really an elementary particle?
- How exactly are quarks and gluons confined?
- Why is there something rather than nothing?
- Why three generations? And why just those masses?
- How do neutrinos get their masses?
- Why is there something rather than nothing?
  (more matter than antimatter)
- What is dark matter?
- What the $%!=* is dark energy?
  (or why did particle physics get it so horribly wrong?)
- Can we find a theory of quantum gravity?
- Can particle physics explain the Big Bang?

Open questions

- Is the Higgs boson really an elementary particle?
- How exactly are quarks and gluons confined?
- Why is there something rather than nothing?
- Why three generations? And why just those masses?
- How do neutrinos get their masses?
- Why is there something rather than nothing?
  (more matter than antimatter)
- What is dark matter?
- What the $%!=* is dark energy?
  (or why did particle physics get it so horribly wrong?)
- Can we find a theory of quantum gravity?
- Can particle physics explain the Big Bang?
- **Add your own questions here!**