IOP Institute of Physics

Stuff: What is it?... An Introduction to Particle Physics and the LHC

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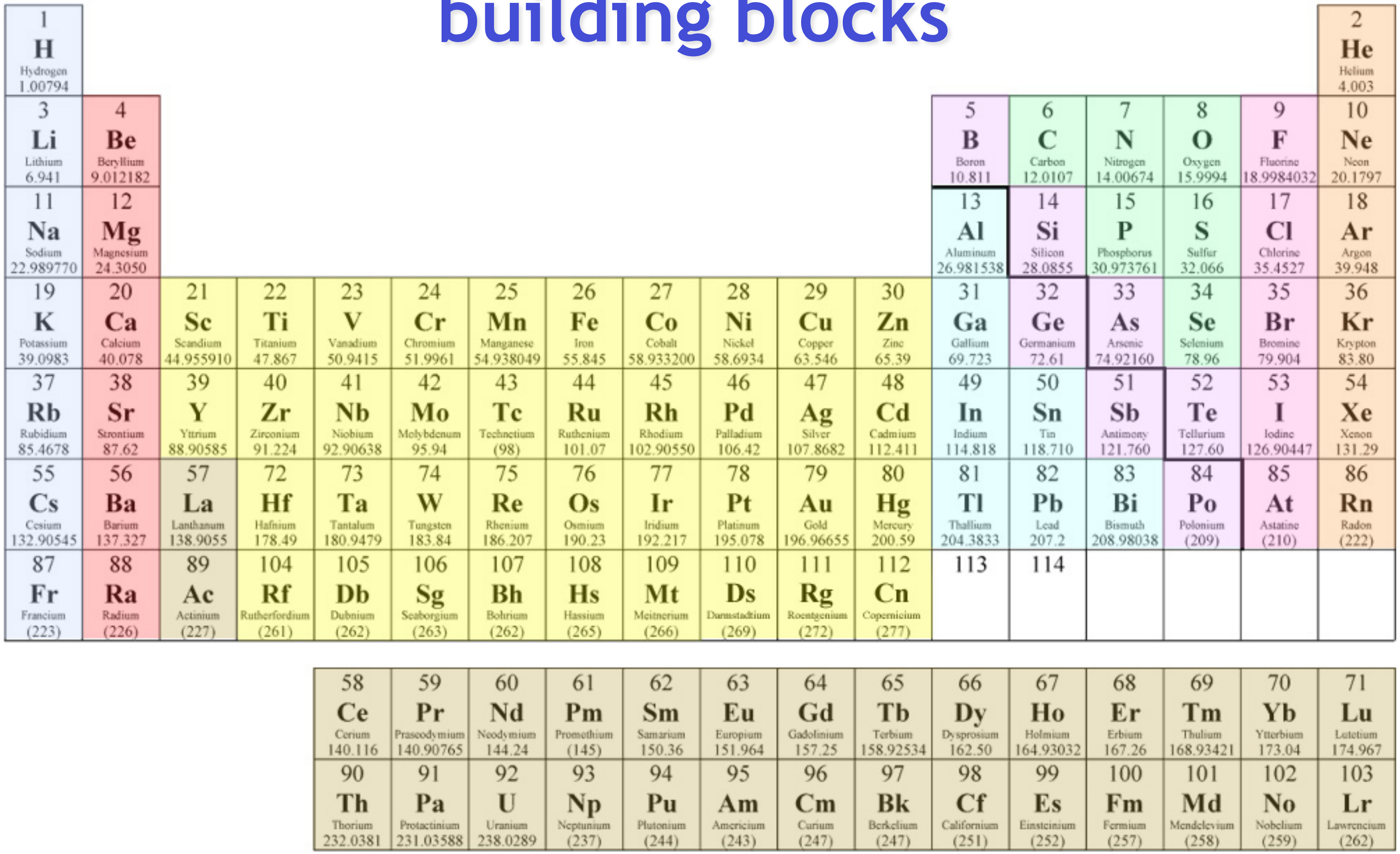
UNIVERSITY OF BIRMINGHAM

IOP Lecture, 4 October 2011

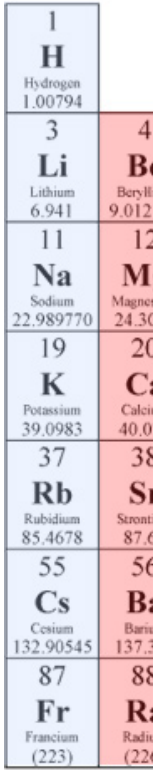
Late 19th Century: Atoms as nature's basic building blocks

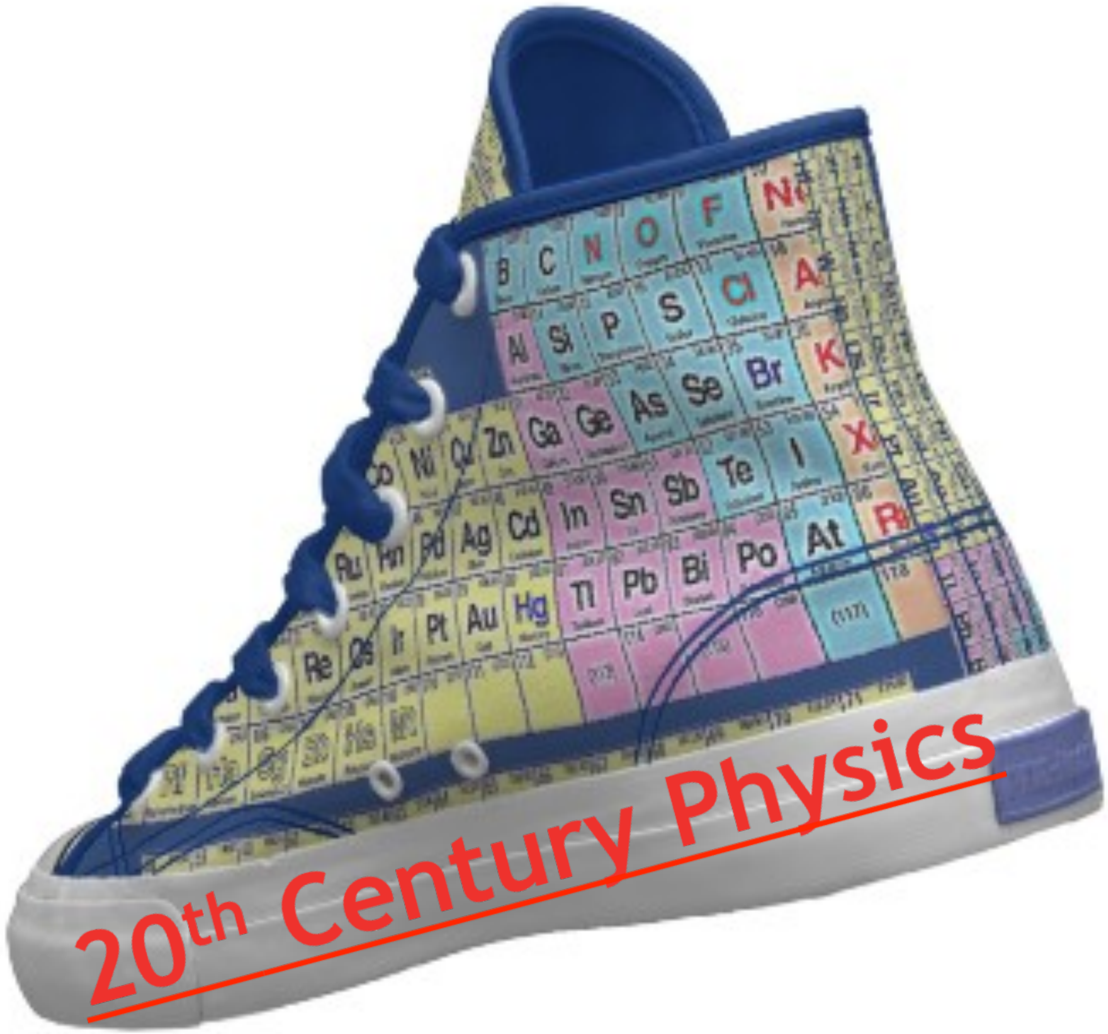


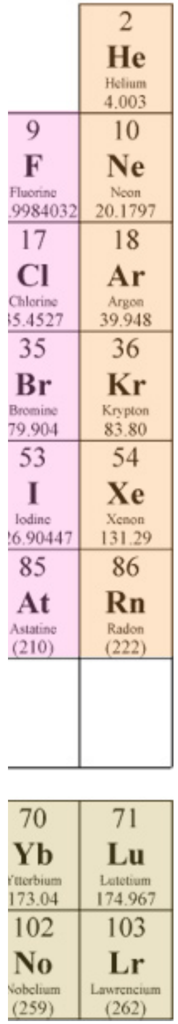
"There is nothing new to be discovered in physics now,
All that remains is more and more precise measurement."

Lord Kelvin, 1900

Late 19th Century: Atoms as nature's basic building blocks





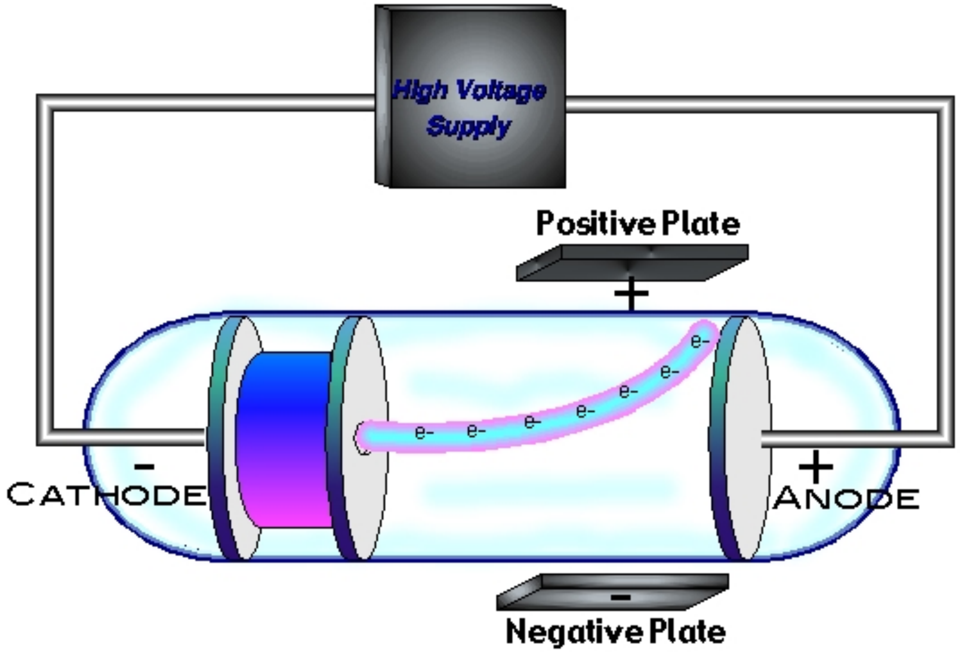


A much deeper (and simpler) structure has been revealed in collisions of very high energy particles at accelerators

Cathode Ray Tubes

High Voltage passed across low pressure gas

Mysterious charged particles emitted from cathode



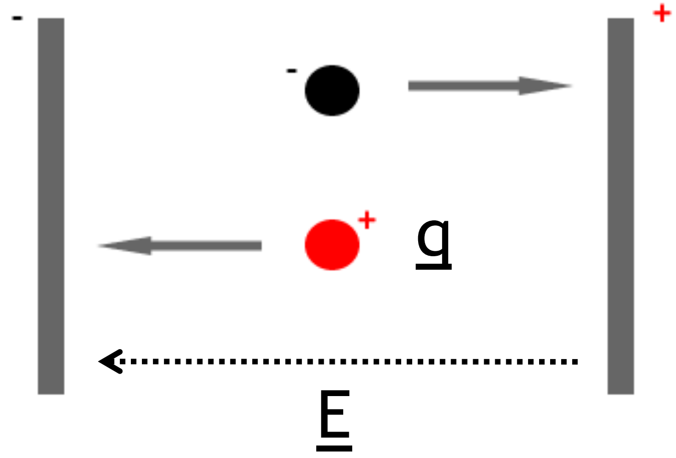
1897: JJ Thompson measured cathode ray mass from bending in electric field

… 1/1000th of mass of Hydrogen
… there are smaller things than atoms!
… we now know them as 'electrons'

How does a Cathode Ray Tube work?

We can accelerate charged particles by applying an electric field to them

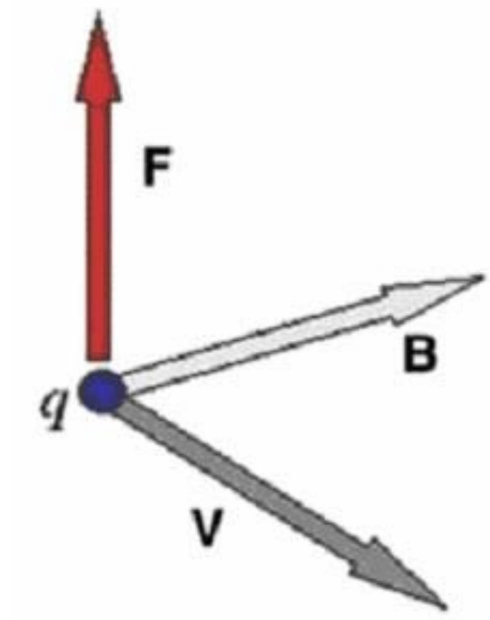
$$F = ma = qE$$



We can also change the direction of the particle by applying magnetic fields

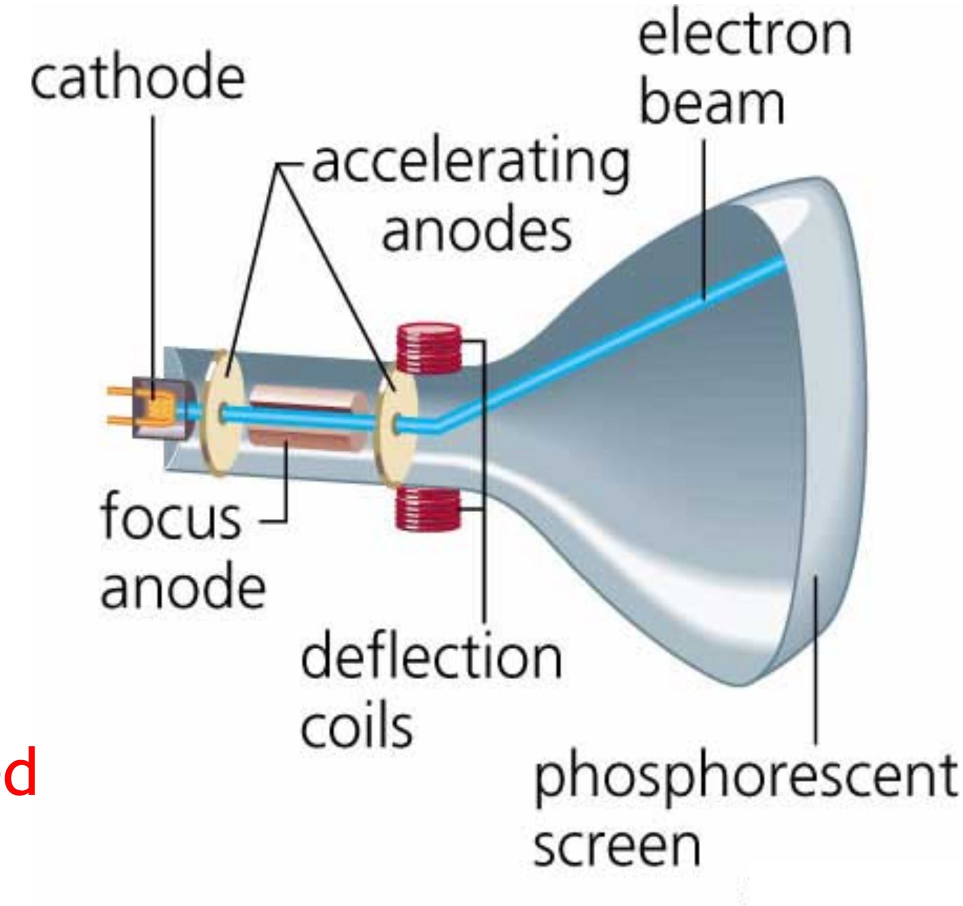
$$F = ma = qvB$$

... acting perpendicular to the B field and the particle's motion



Another Cathode Ray Tube: The Telly!

- Accelerate electrons with electric fields
- Bend them in magnetic fields
- Image on light-emitting screen



Particle physics accelerators are giant cathode ray tubes!

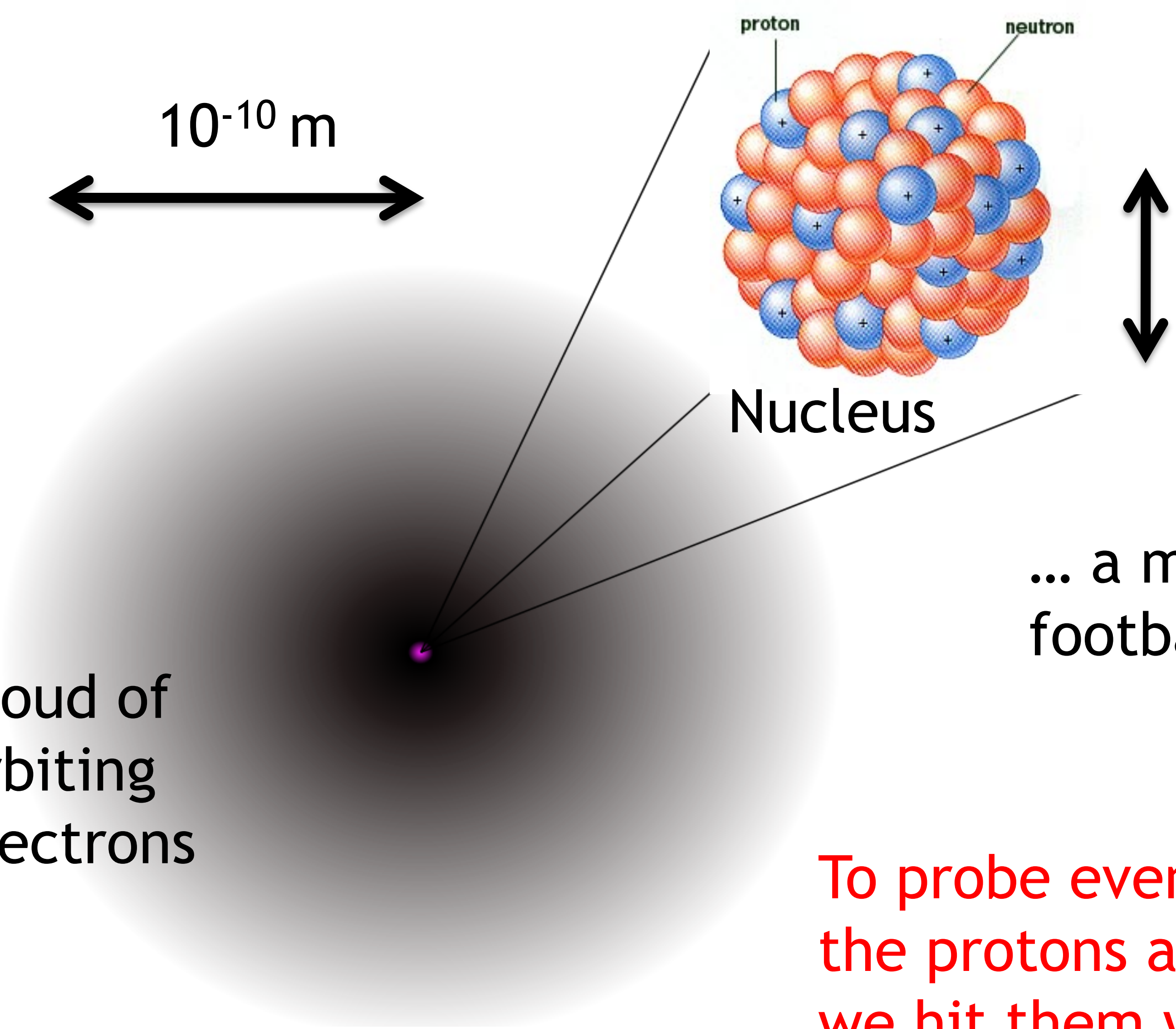
<u>**A USEFUL UNIT**</u>

A particle of charge q accelerated through a potential difference V acquires a kinetic energy KE=qV.

1 volt gives an electron an energy of 1 electron-volt (eV)

- A cathode ray tube TV accelerates electrons to ~ 20,000 eV
- The Large Hadron Collider accelerates protons to 7 trillion eV

A Modern Picture of the Atom



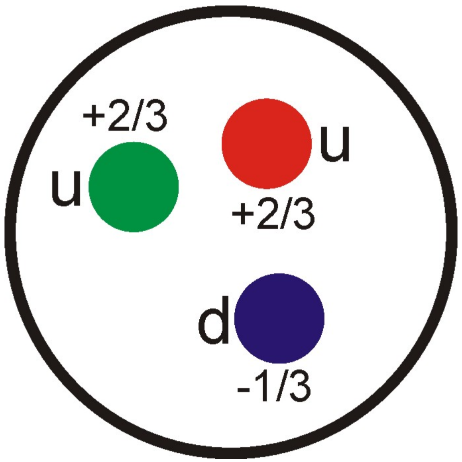
… a marble in a football stadium …

To probe even deeper inside the protons and neutrons, we hit them with very high energy particles …

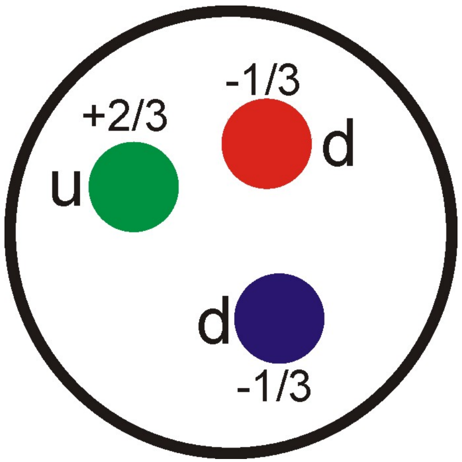
The Modern Picture of Protons and Neutrons

In 1969, an experiment using a 2-mile long 20 GeV electron accelerator showed that protons have structure → "quarks"

- Protons and neutrons made from Up (u) and Down (d) quarks.
- u-quarks have +2/3 of electron charge, d-quarks have –1/3



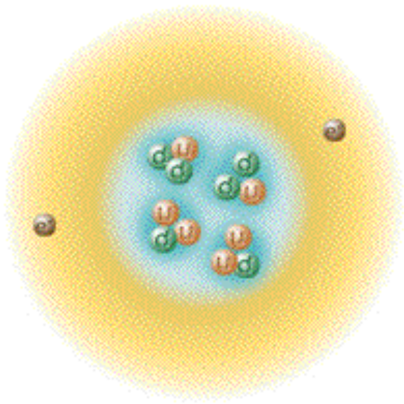
Proton



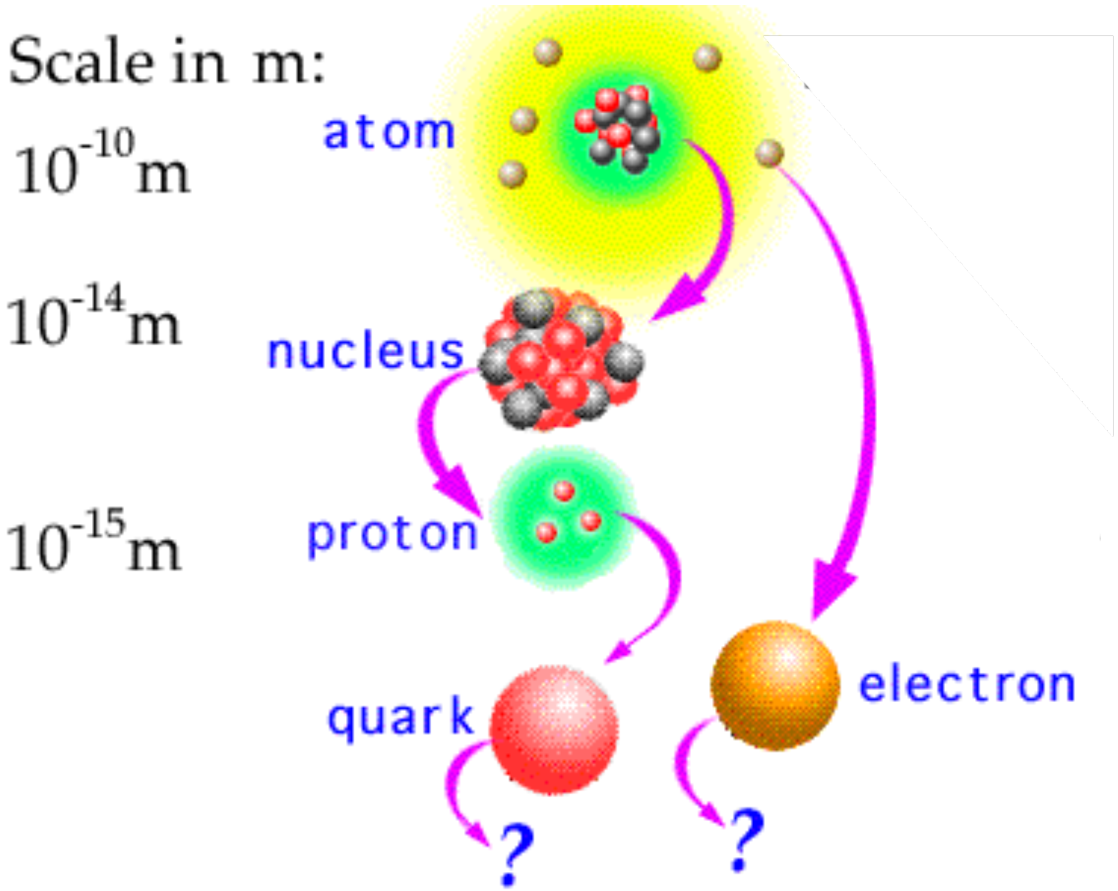
Neutron

So What is ‘Stuff’ Ultimately Made of?

• All matter around us is made of atoms.
• Positive nucleus (99.98% of mass) and a cloud of electrons.

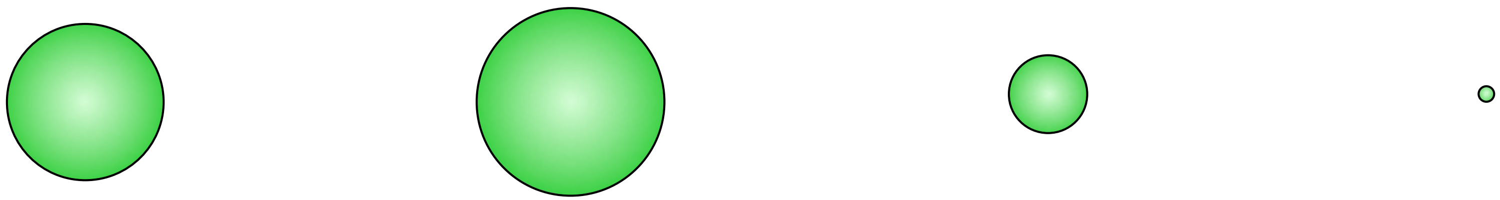


• Nuclei consist of protons and neutrons.
• The protons and neutrons are made of quarks.



… A Nice Happy Family of Particles

Up quark (u) | **Down quark (d)** | **Electron (e^-)** | **Electron neutrino (ν_e)**



Mass ~ 0.003 | ~ 0.006 | = 0.0005 | ~ 10^{-8} ?

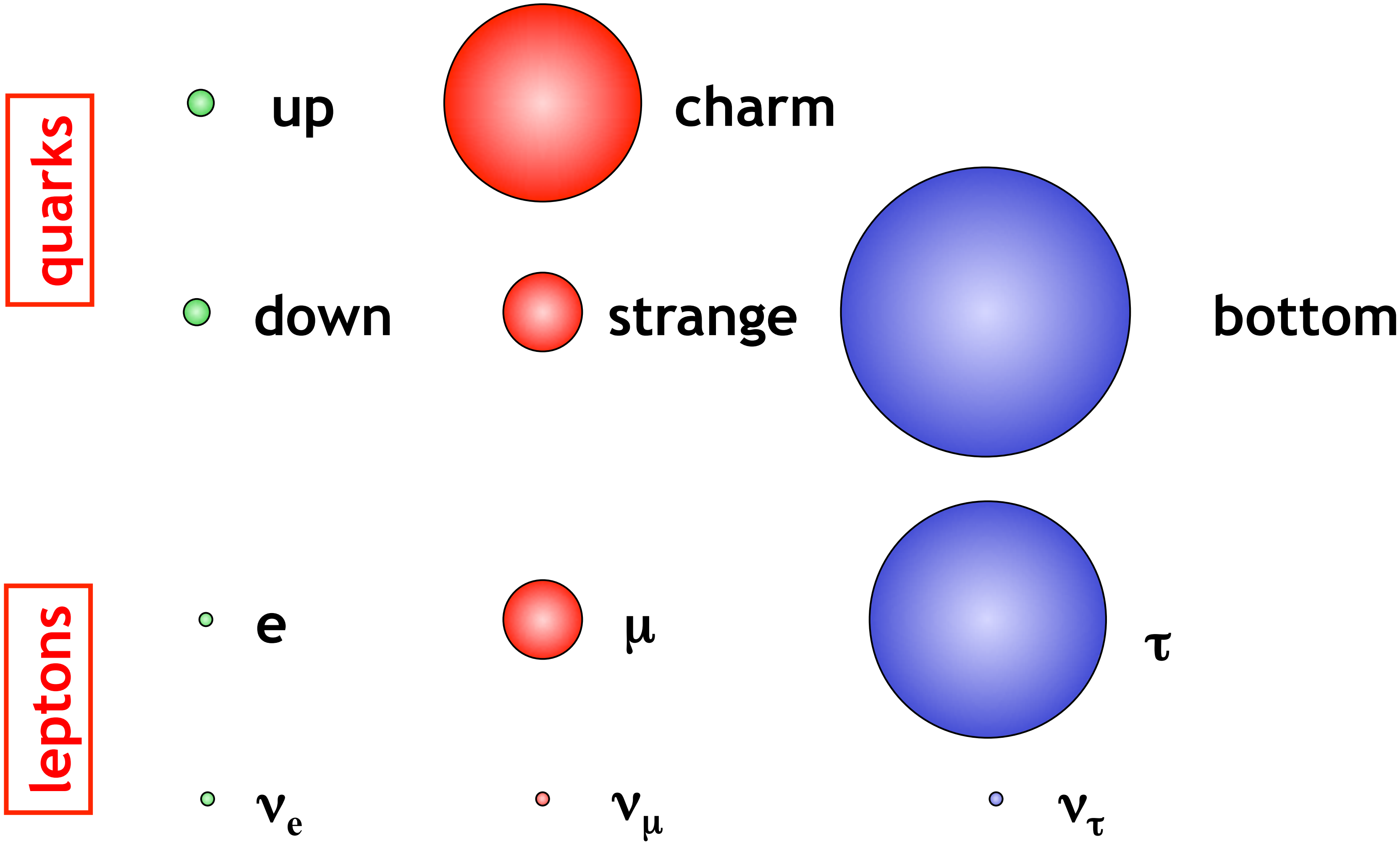
(relative to the mass of a single proton)

Everything around us (the whole Periodic Table) is made of up quarks, down quarks and electrons.

… but for some reason, there is more …

Nature supplies us with a copy of the family … but heavier …

… and another copy of the family … but even heavier …



The Top Quark

Discovered in 1995 …

Weighs about the same as a gold nucleus!

… and that is where it seems to stop

Why the heavy copies of the basic building blocks?

What about Antimatter?

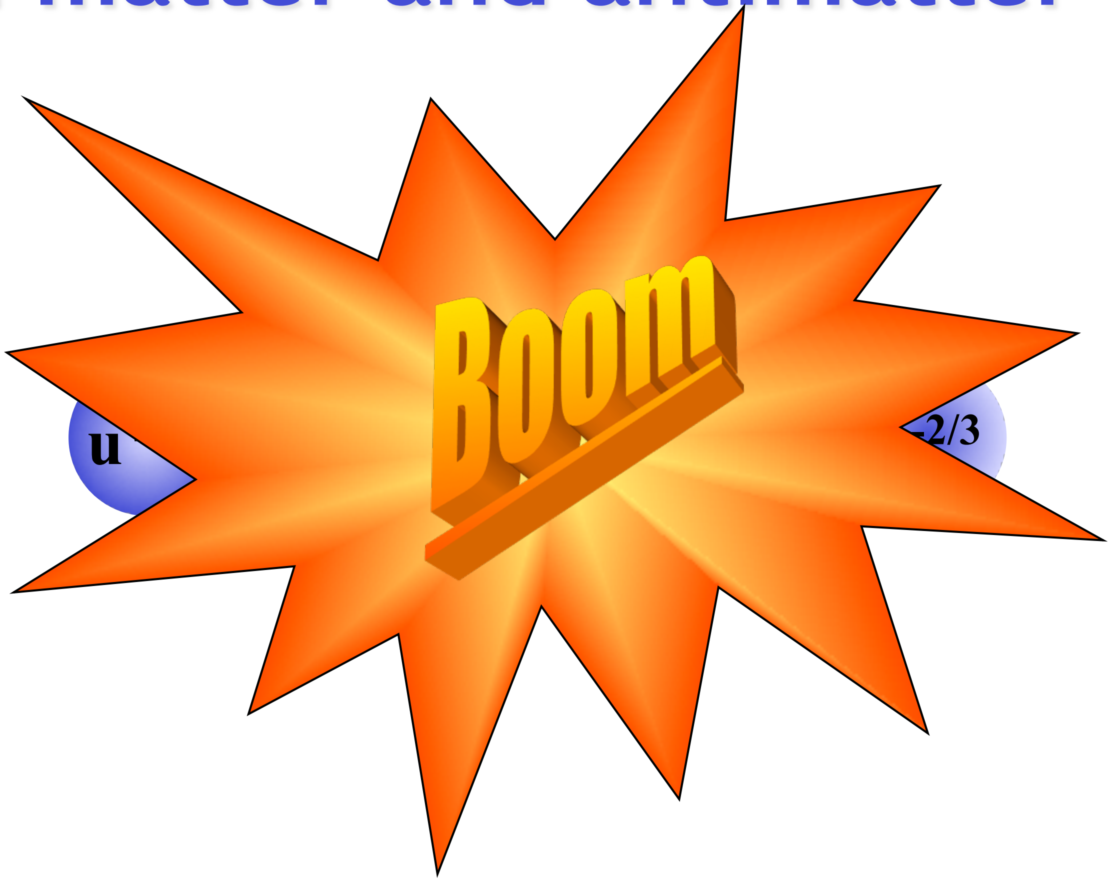
1928: Paul Dirac discovered the theory of the electron …
but it also predicted anti-electrons (`positrons')

Every fundamental particle has an antiparticle, with the same mass, but opposite charge.

electron	e^-	e^+	positron
up quark	$u^{+2/3}$	$\bar{u}^{-2/3}$	up anti-quark

etc etc …

When matter and antimatter meet …



• If a particle and an antiparticle, each of mass m, collide, they annihilate, producing energy <u>$E = 2mc^2$</u>

• That energy can be used to produce new (perhaps undiscovered?) particles …

What about the Forces?

3 important forces in particle physics (gravity is just too weak) …

1) Electrostatic and magnetic forces are different aspects of a single electromagnetic force

$$F = \frac{1}{4\pi\varepsilon_0} \frac{q_1 q_2}{r^2}$$

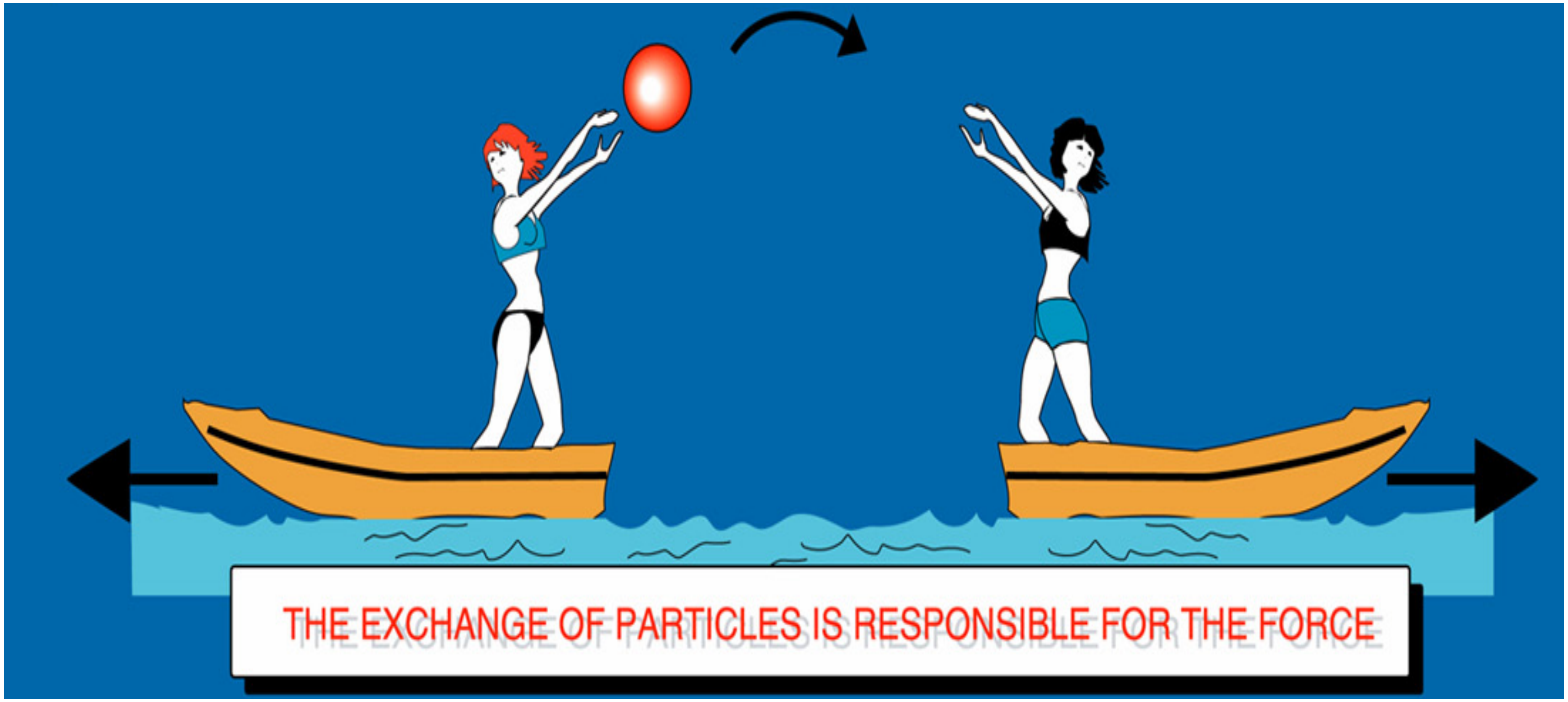
2) The strong nuclear force holds the quarks together in the protons and neutrons … so that they can't escape …

$$F = \text{const.}$$

3) The weak nuclear force is responsible for nuclear β decay: close relative of electromagnetic force … but short range …

The Particle Physics view of Forces

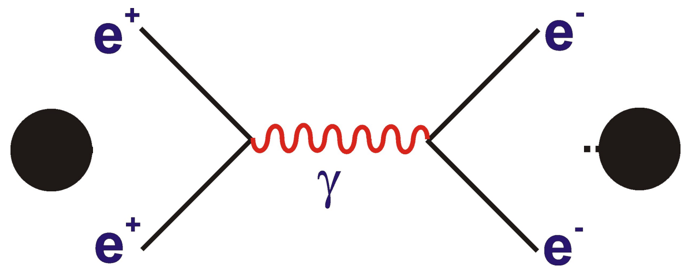
The microscopic view: forces also caused by particles
… being exchanged between the matter particles



The Force Carriers

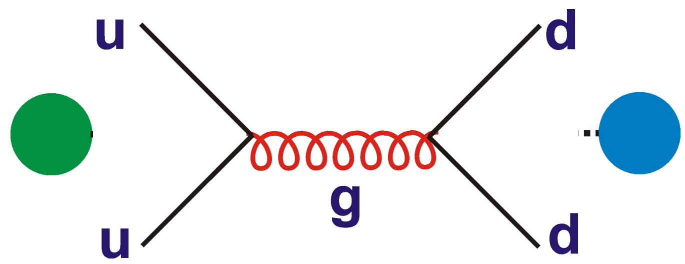
1) Electromagnetic force

<u>PHOTON EXCHANGE</u>



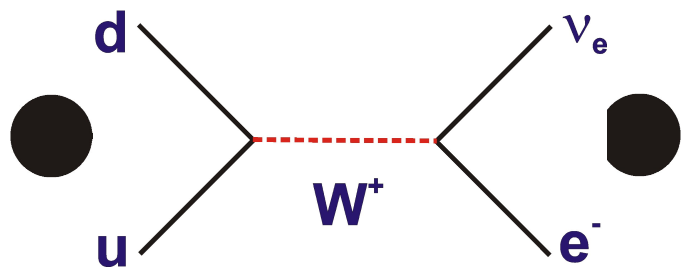
2) Strong nuclear force

<u>GLUON EXCHANGE</u>



3) Weak nuclear force

<u>Z^0, W^+, W^- EXCHANGE</u>



Short range because W and Z bosons are HEAVY:

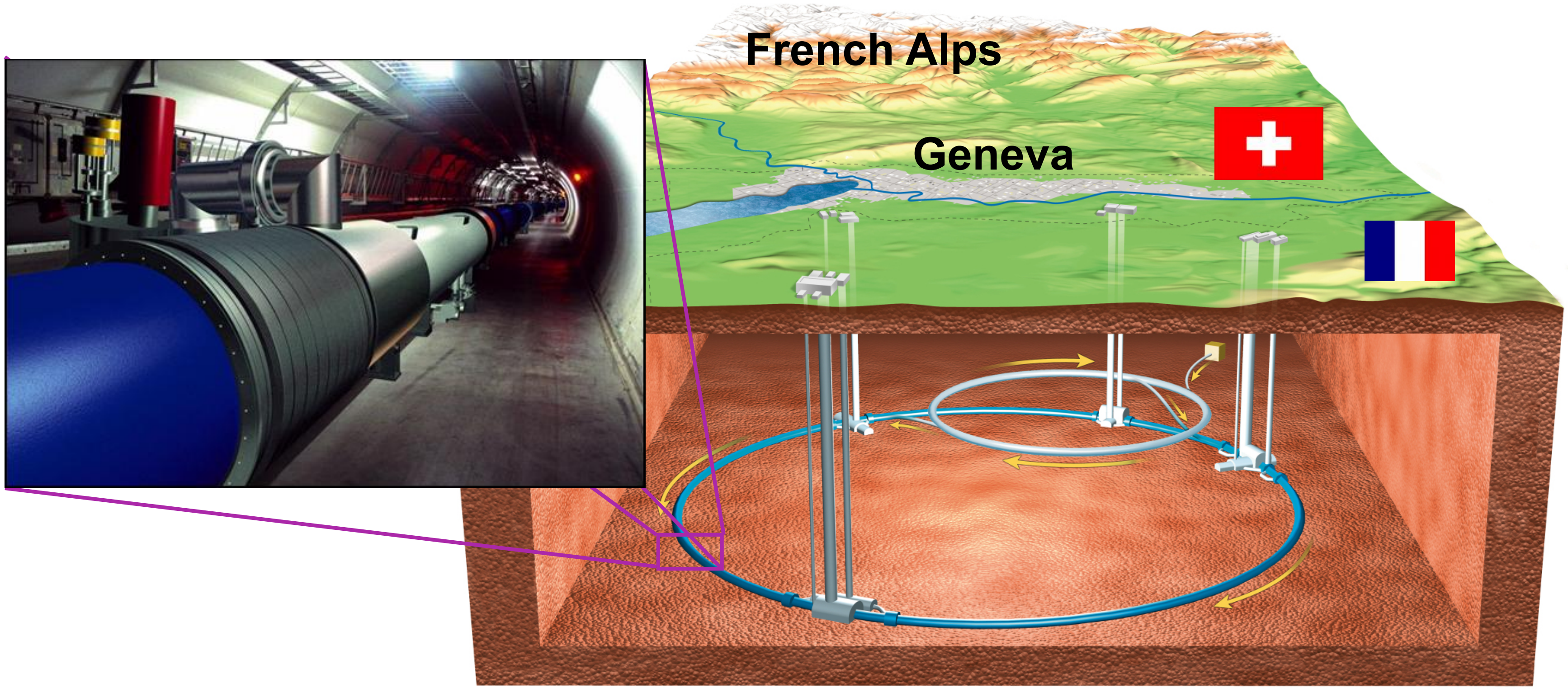
… 80-90 times heavier than a proton!

→ The present day …
on the Swiss French Border …

… near Lake Geneva, between the Alps and the Jura

… is the world's largest Physics Laboratory

… what CERN is currently doing …

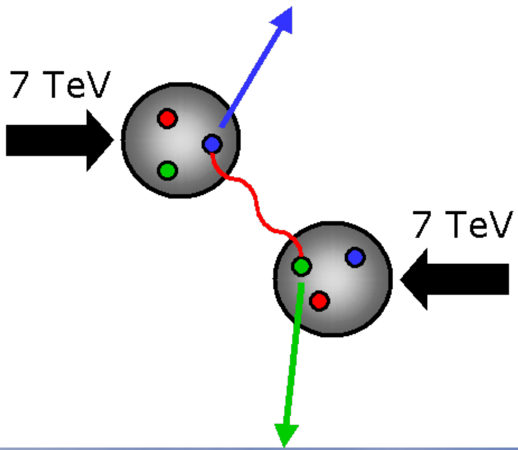


The Large Hadron Collider (LHC)

100m underground … in a 27km long tunnel…
… accelerates protons to 0.99999996 of the speed of light.

The LHC Beams

Colliding protons with 7 TeV each (7×10^{12} = 7 trillion electron-volts)

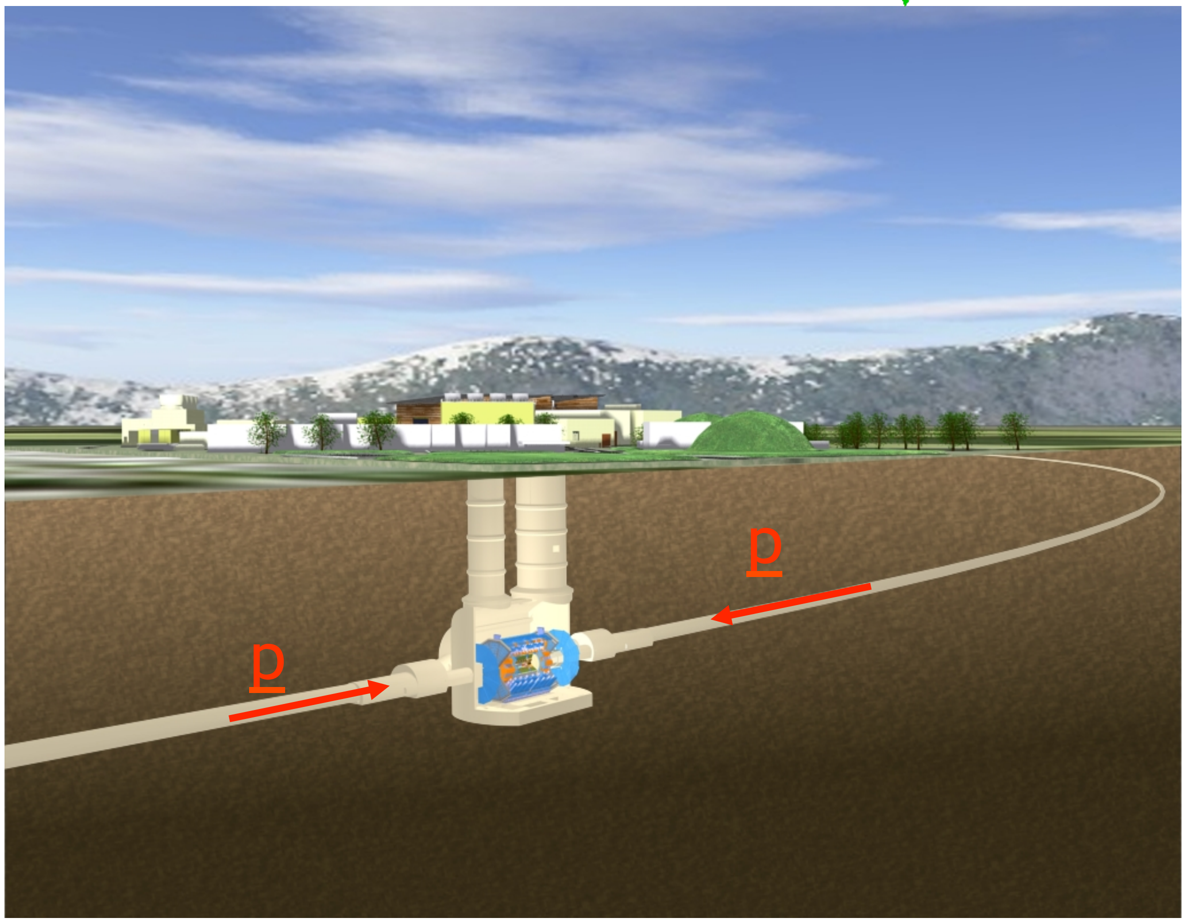


- Each proton goes round ring 11,000 times per Second.

- 10^{11} protons per bunch, with 40 million bunch crossings per second

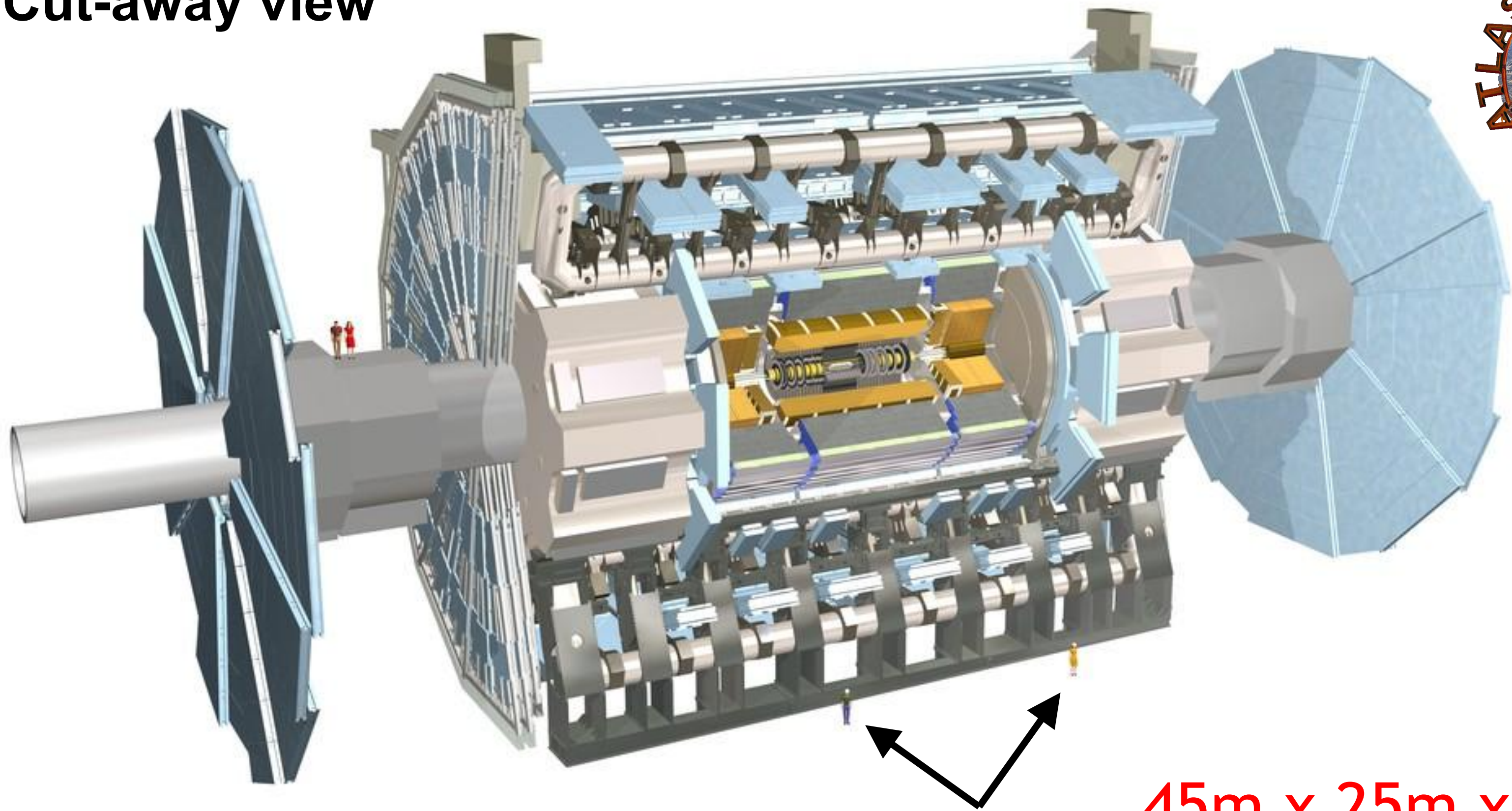
- Total stored energy of 300 MJ … equivalent to a family car at 1000 mph

- Ring looks just 4m long to the protons!



Detecting the Results of the Collisions

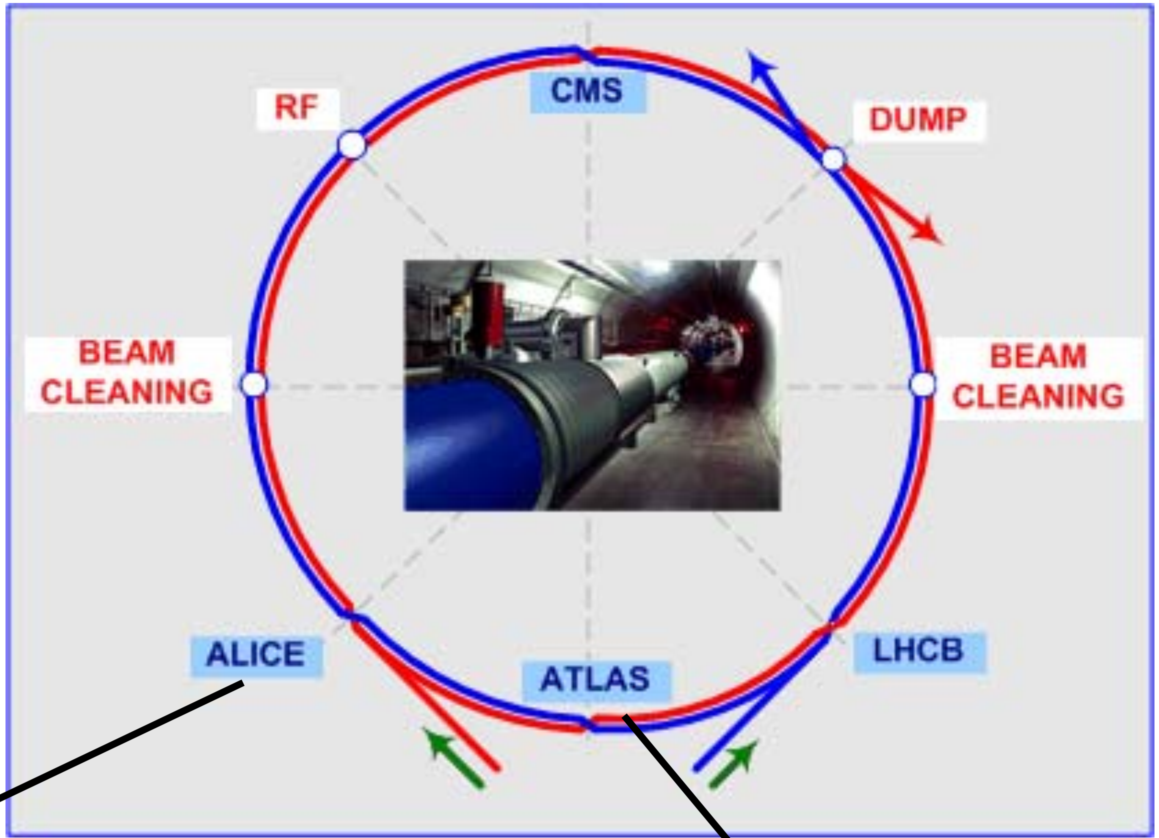
The protons or ions collide in four cathedral sized caverns, creating conditions and particles which have not existed since a fraction of a second after the big bang.



The scientific collaborations are as big as the detectors …
e.g. ATLAS involves ~3000 physicists from 174 institutes in 38 different countries

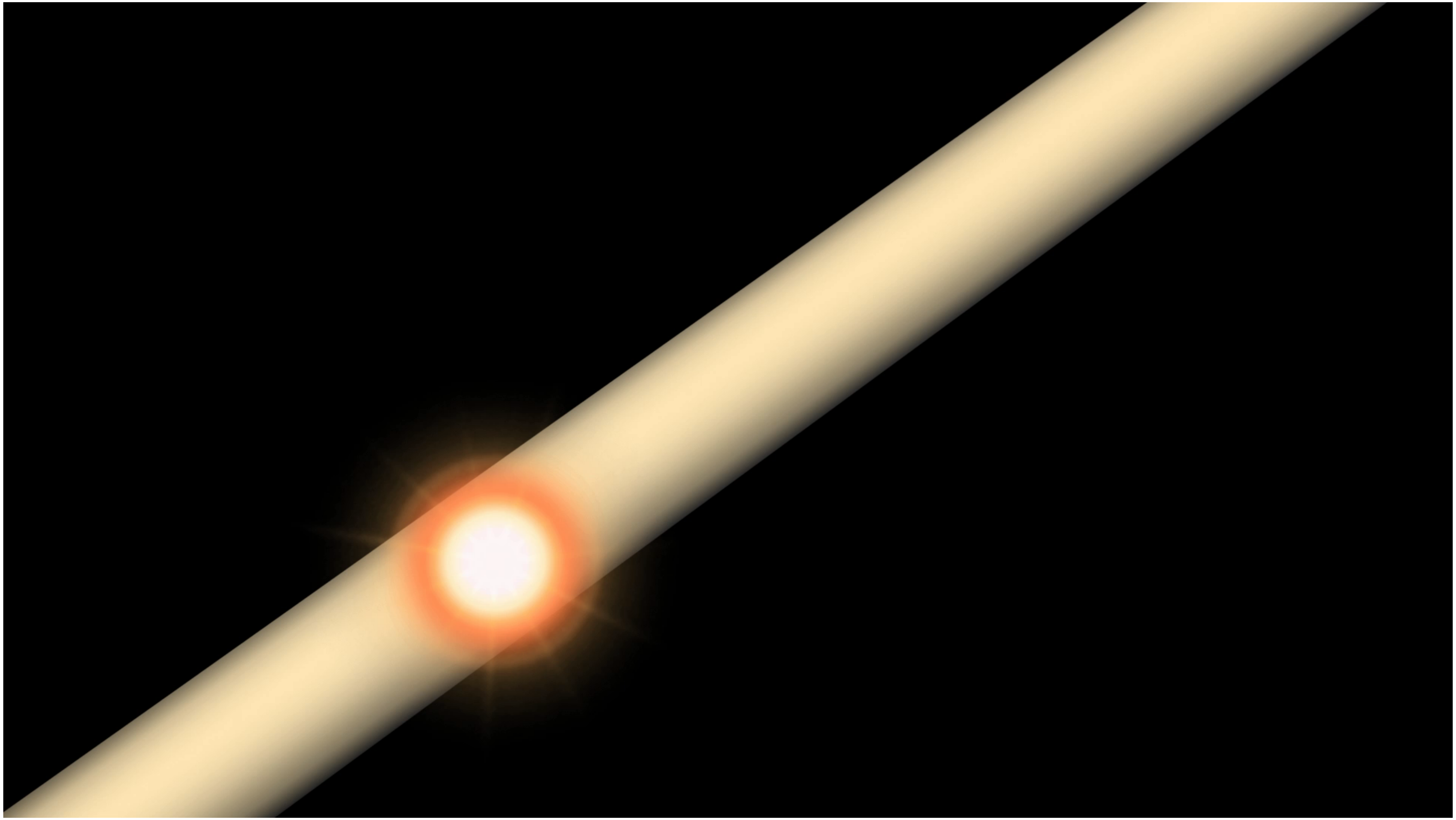
Birmingham & the LHC

Birmingham has large groups, playing important roles in three of the four LHC experiments, ALICE, ALTAS & LHCb



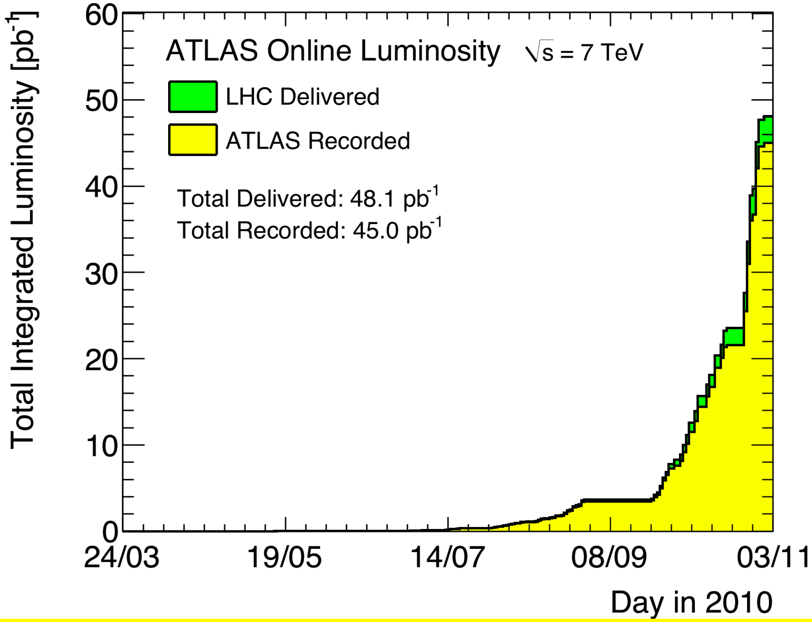
Dave Charlton, ATLAS Deputy Spokesman

David Evans, UK ALICE Spokesman

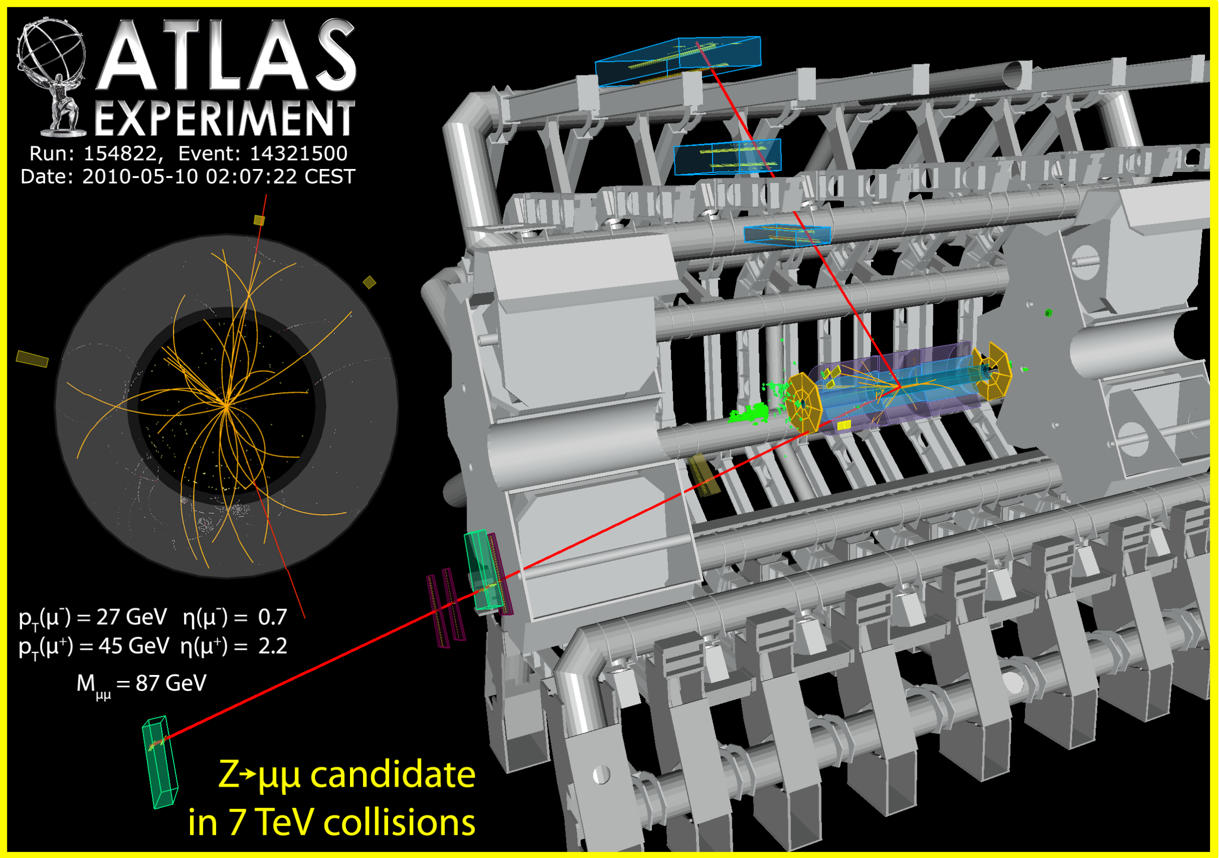


2010: Learning Curves …

… for the LHC: Half of 2010 collisions were delivered in the last week!



… and for the experiments: Learning how the known particles look in the detectors …

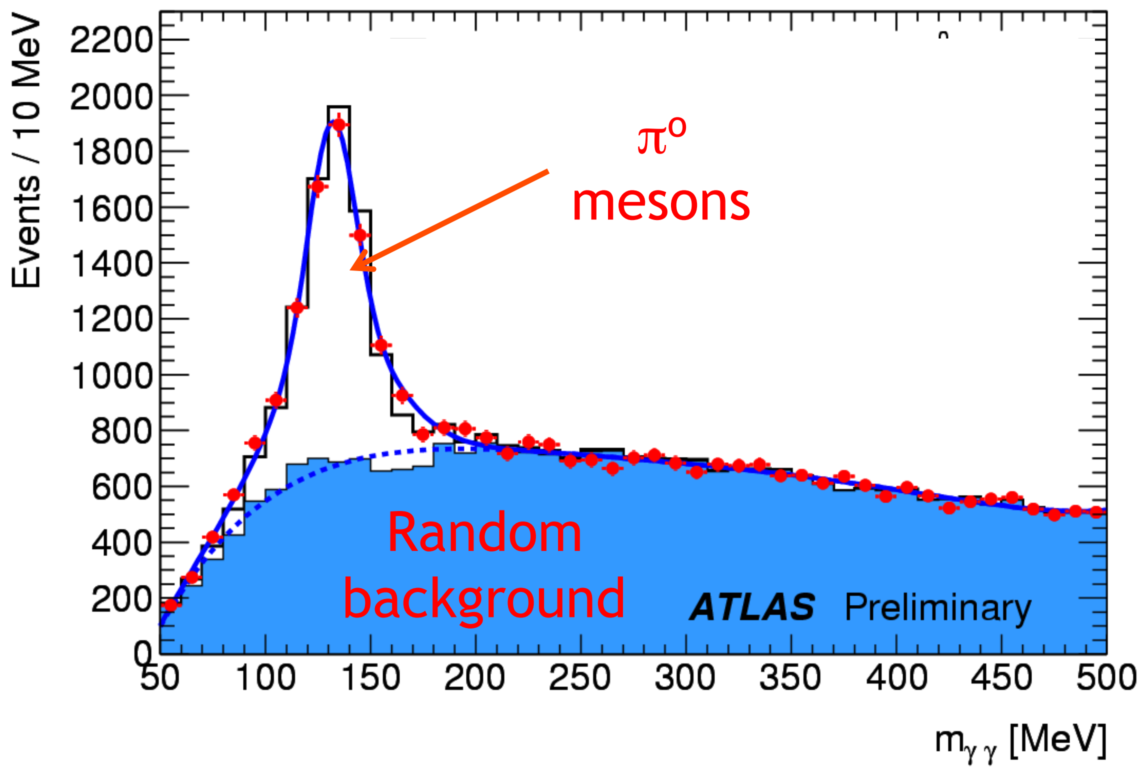


"Seeing" Quarks at the LHC

We can't see the quarks produced in LHC collisions directly
… instead we can see the 'hadrons' that they form together

e.g. a π^0 hadron consists of $u\bar{u}$ or $d\bar{d}$ quarks

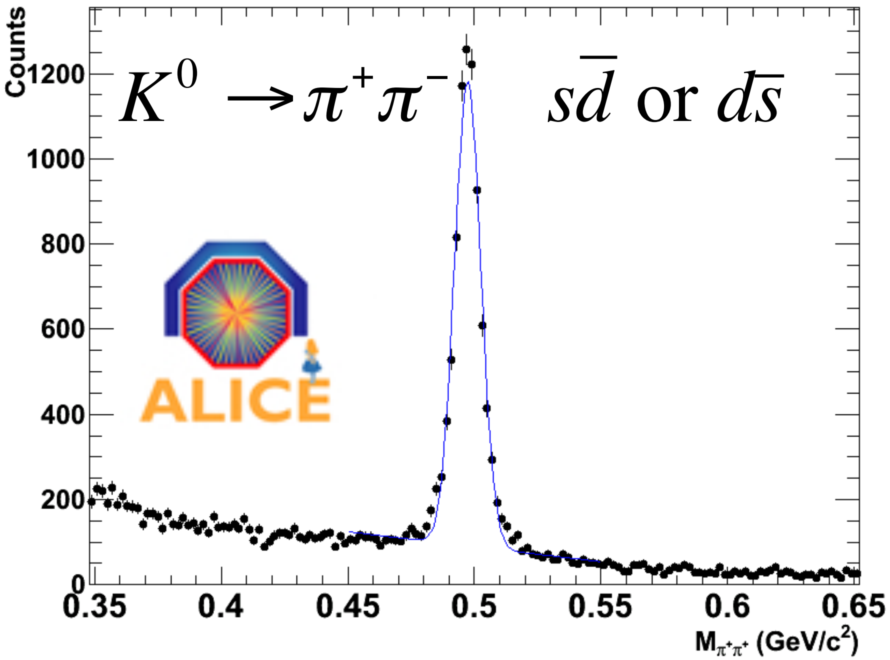
and decays fast to 2 photons ….. $\pi^0 \rightarrow \gamma\gamma$

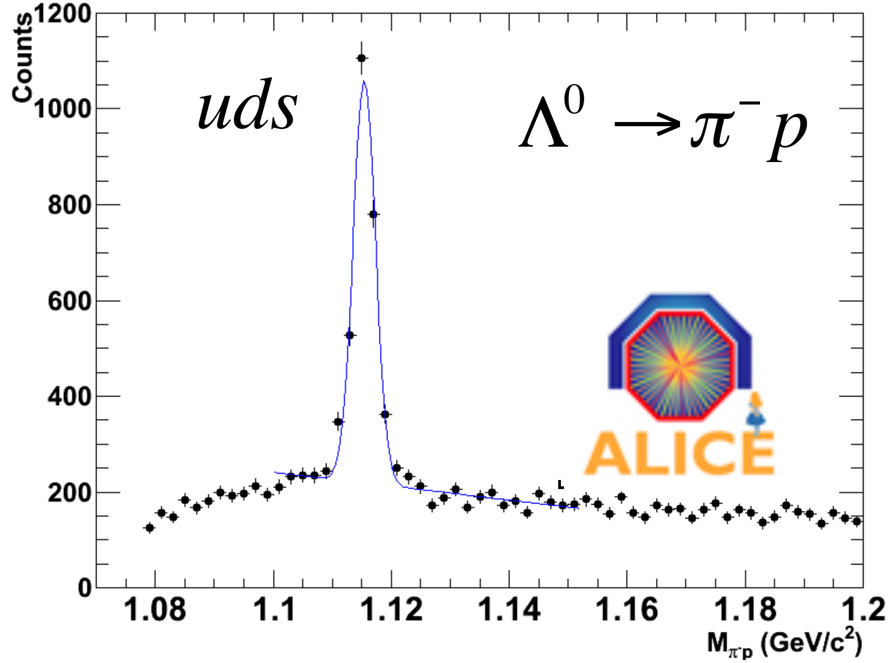


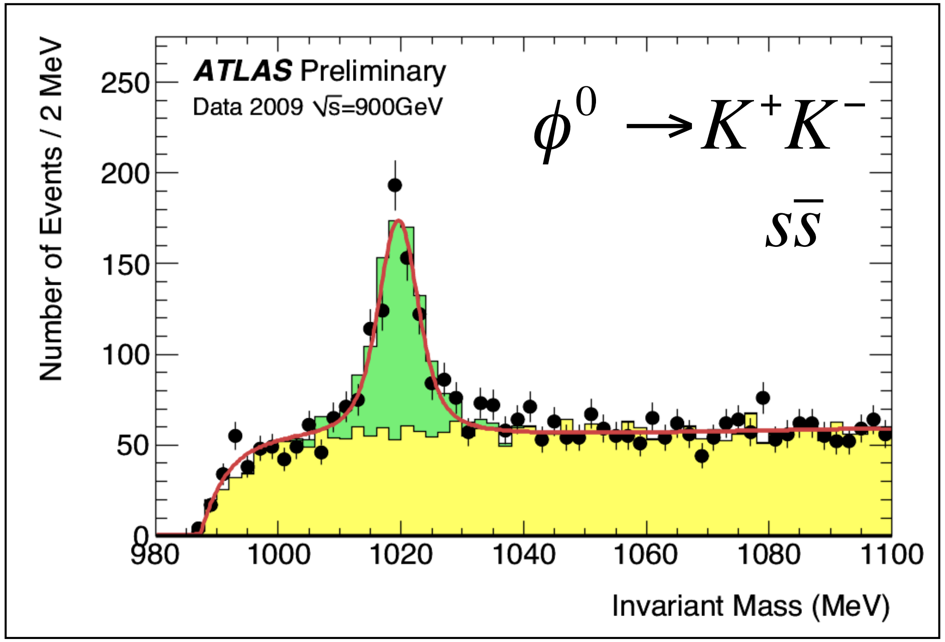
… combine all pairs of photons in every event … look at what particle mass they combine to give …

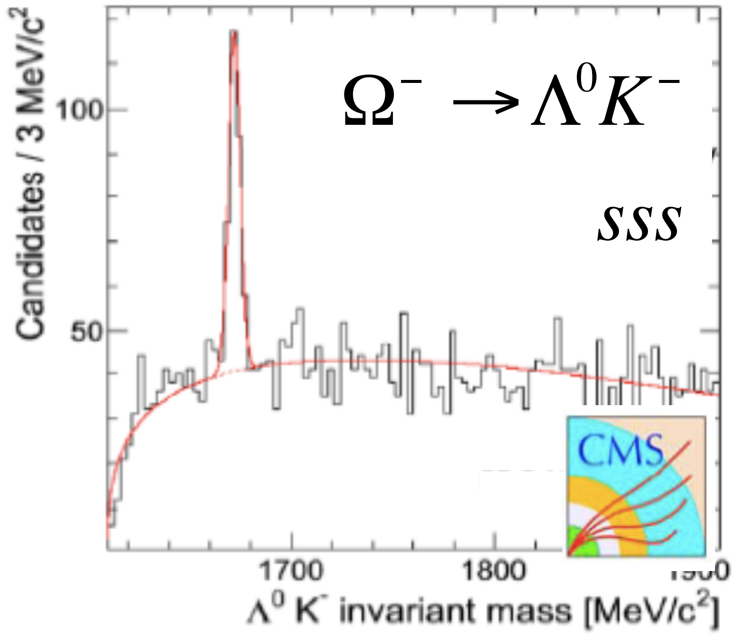
One of the first LHC plots …

Early Strange Particle Sightings

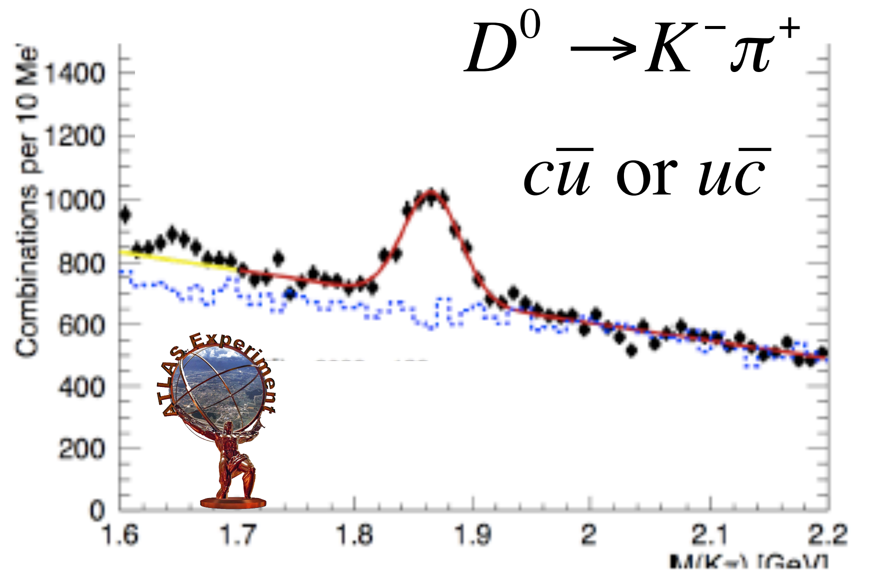


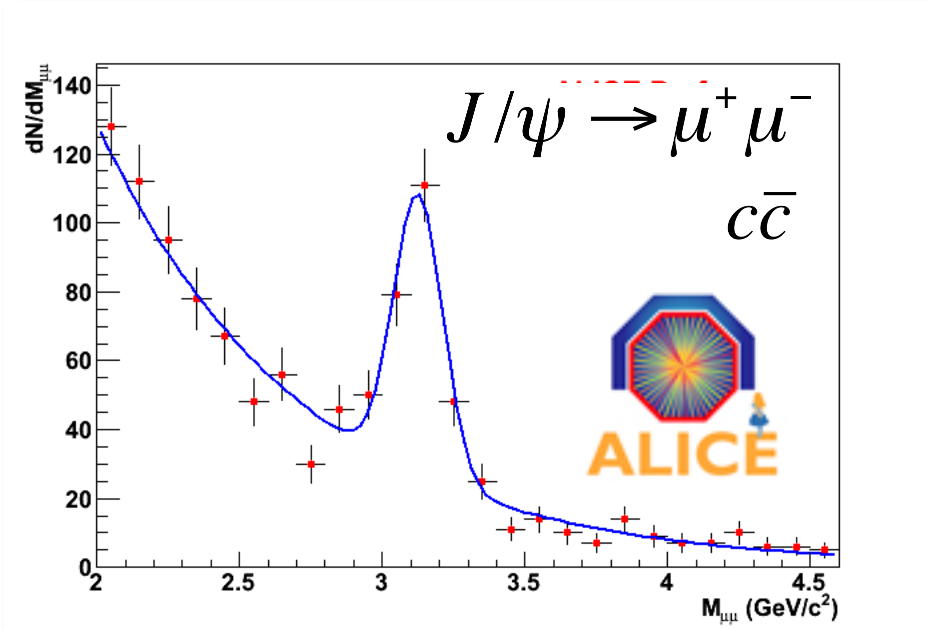


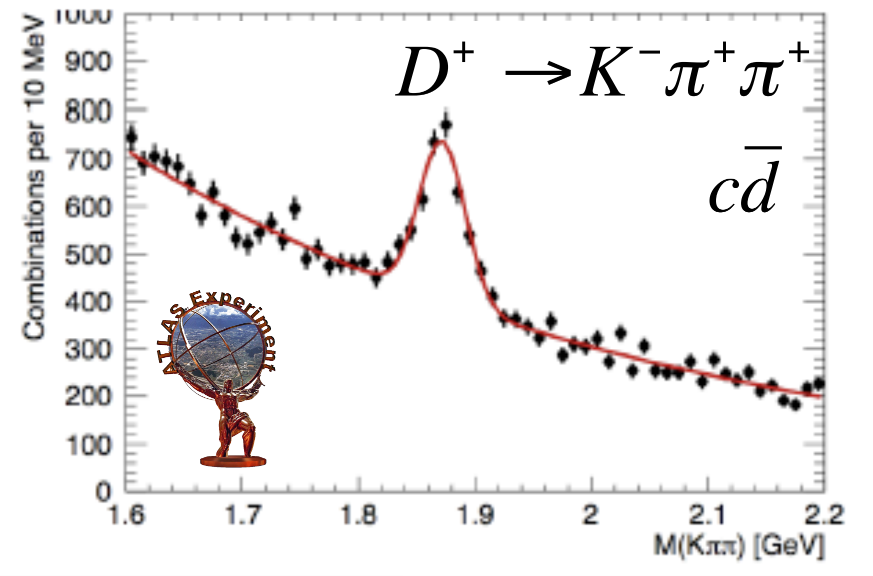


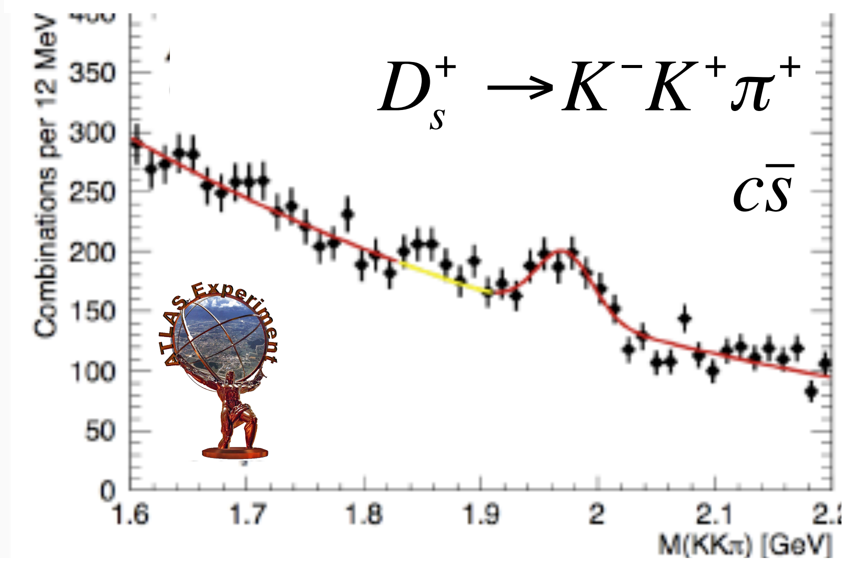


Early Charm Particle Sightings









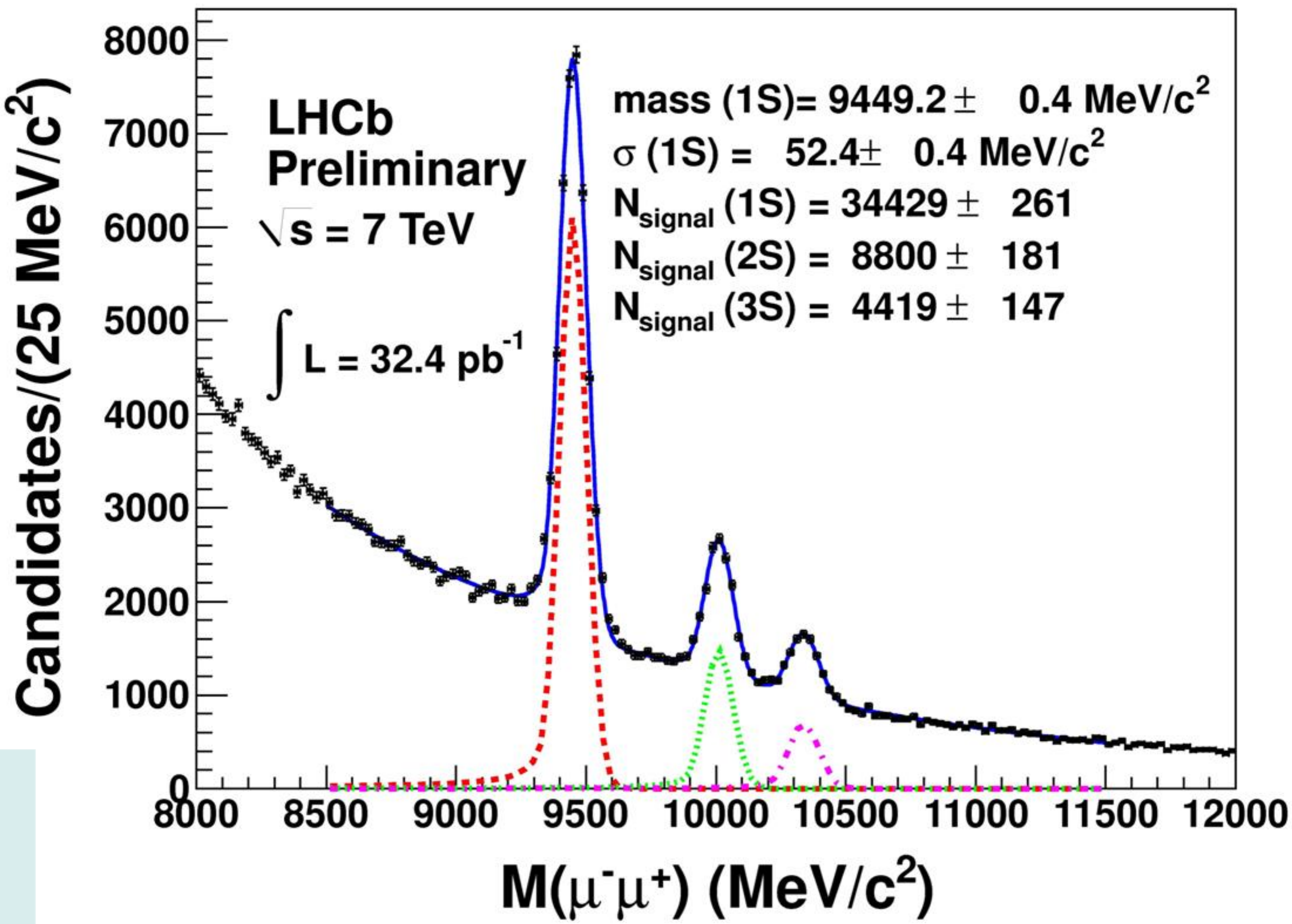
Early Beauty Particle Sightings

3 different $b\bar{b}$ particles

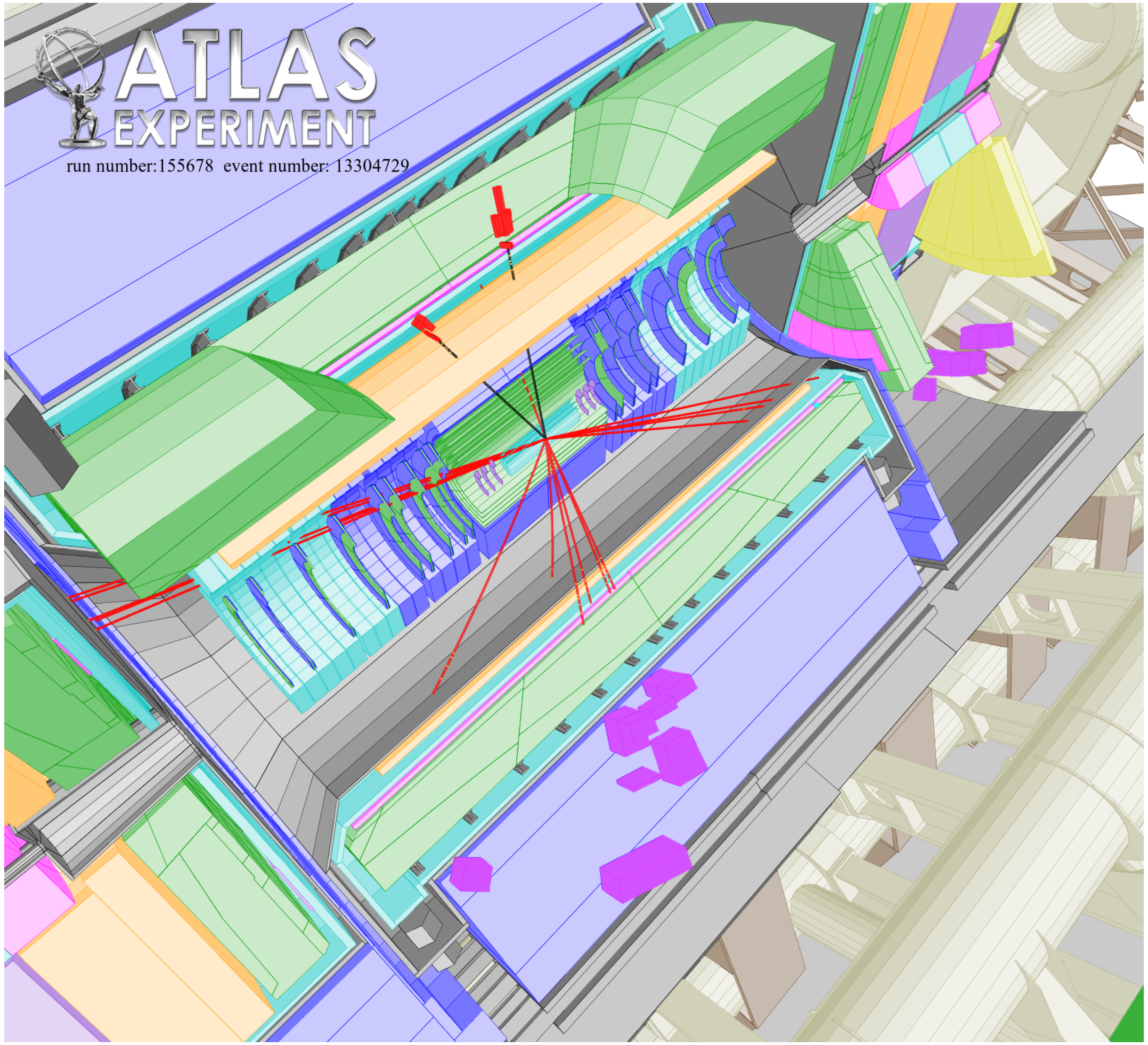
$\Upsilon(1S) \rightarrow \mu^- \mu^+$

$\Upsilon(2S) \rightarrow \mu^- \mu^+$

$\Upsilon(3S) \rightarrow \mu^- \mu^+$



Early Top Quark Sightings



Production of a
top – antitop pair.

The top decays to a
beauty quark and a
W boson.

The W boson decays to
an electron and
its neutrino

… similarly for the
anti-top

Already from 2010 data: Quarks must be smaller than 5×10^{-20} m

2011: The discovery quest begins

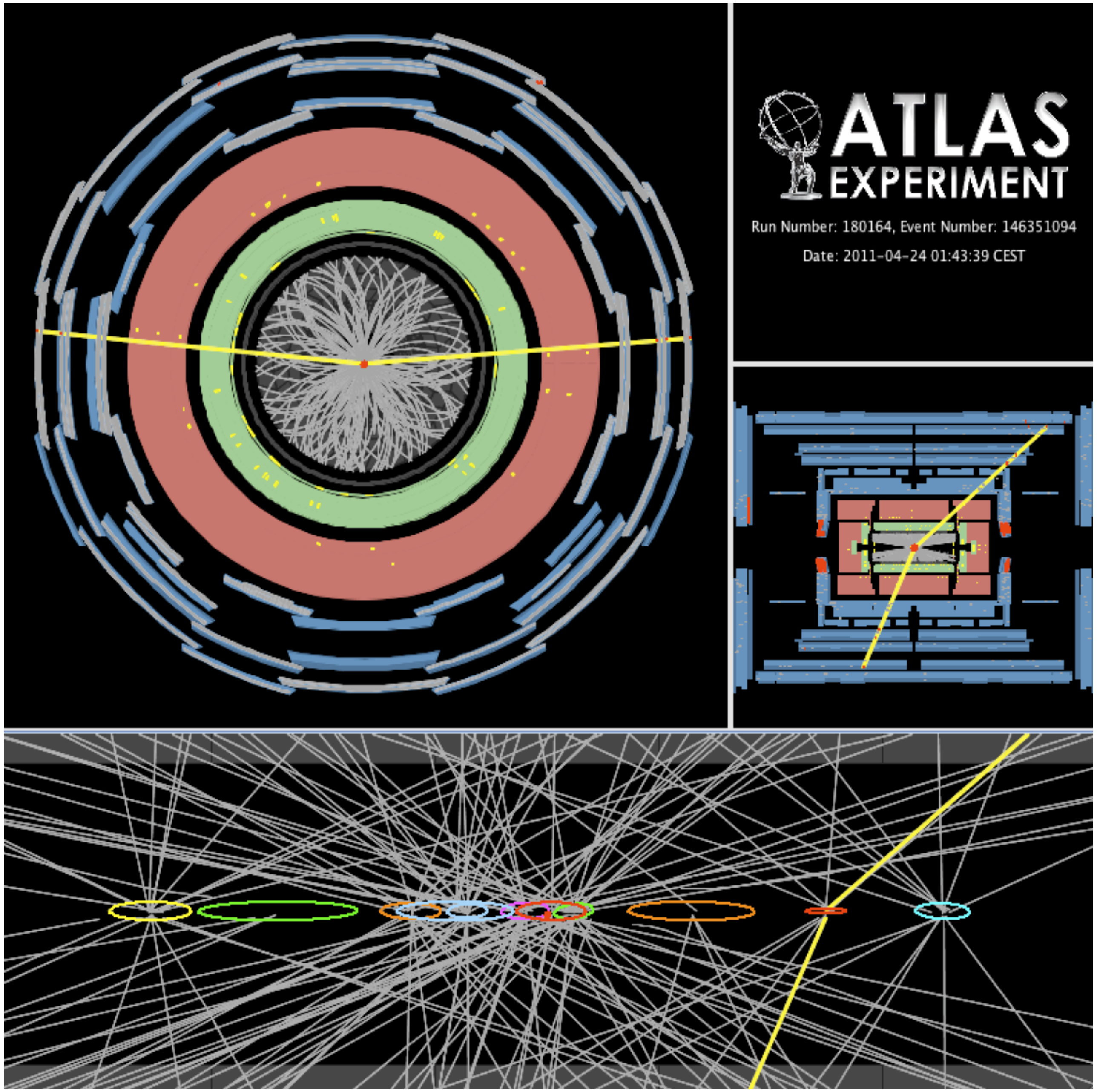
In 2011 we have already collected 70 times more data than 2010
… and the LHC is still running …

… the first serious searches for the unexpected were released for the big physics conferences in the summer …

LEPTON PHOTON 2011
XXV International Symposium on
Lepton and Photon Interactions at High Energies

… already the results have changed our view of physics; full implications are still being understood

… when collision rates start to rise …

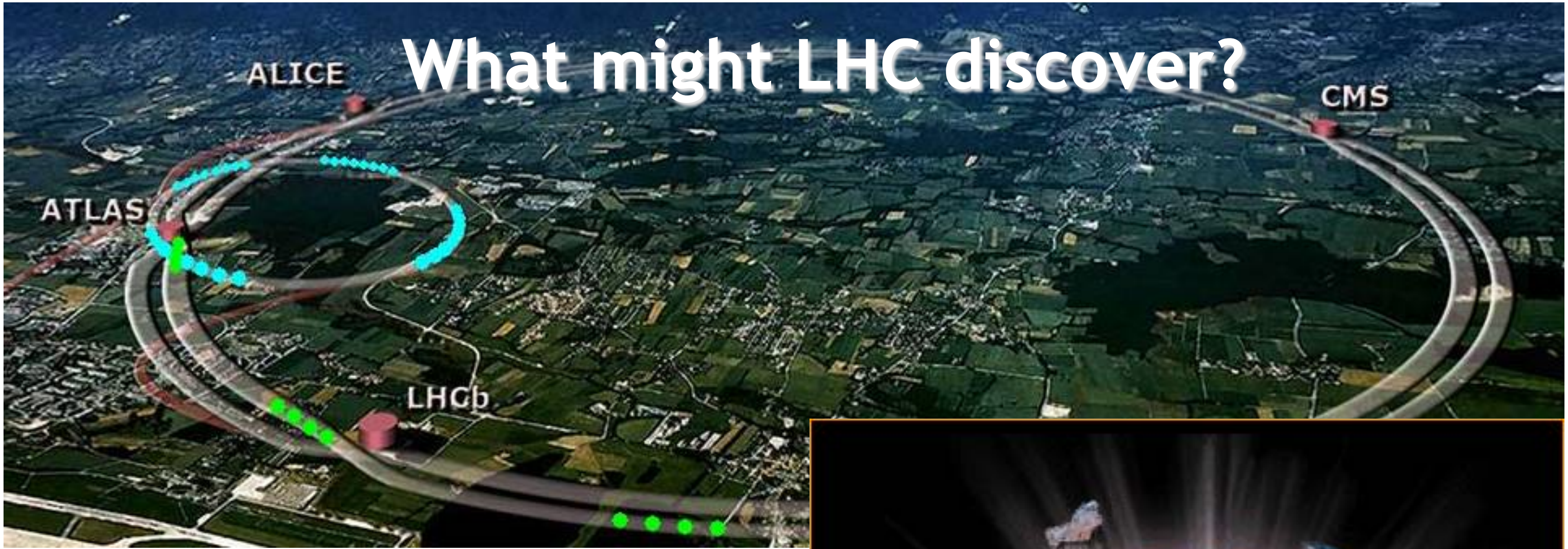


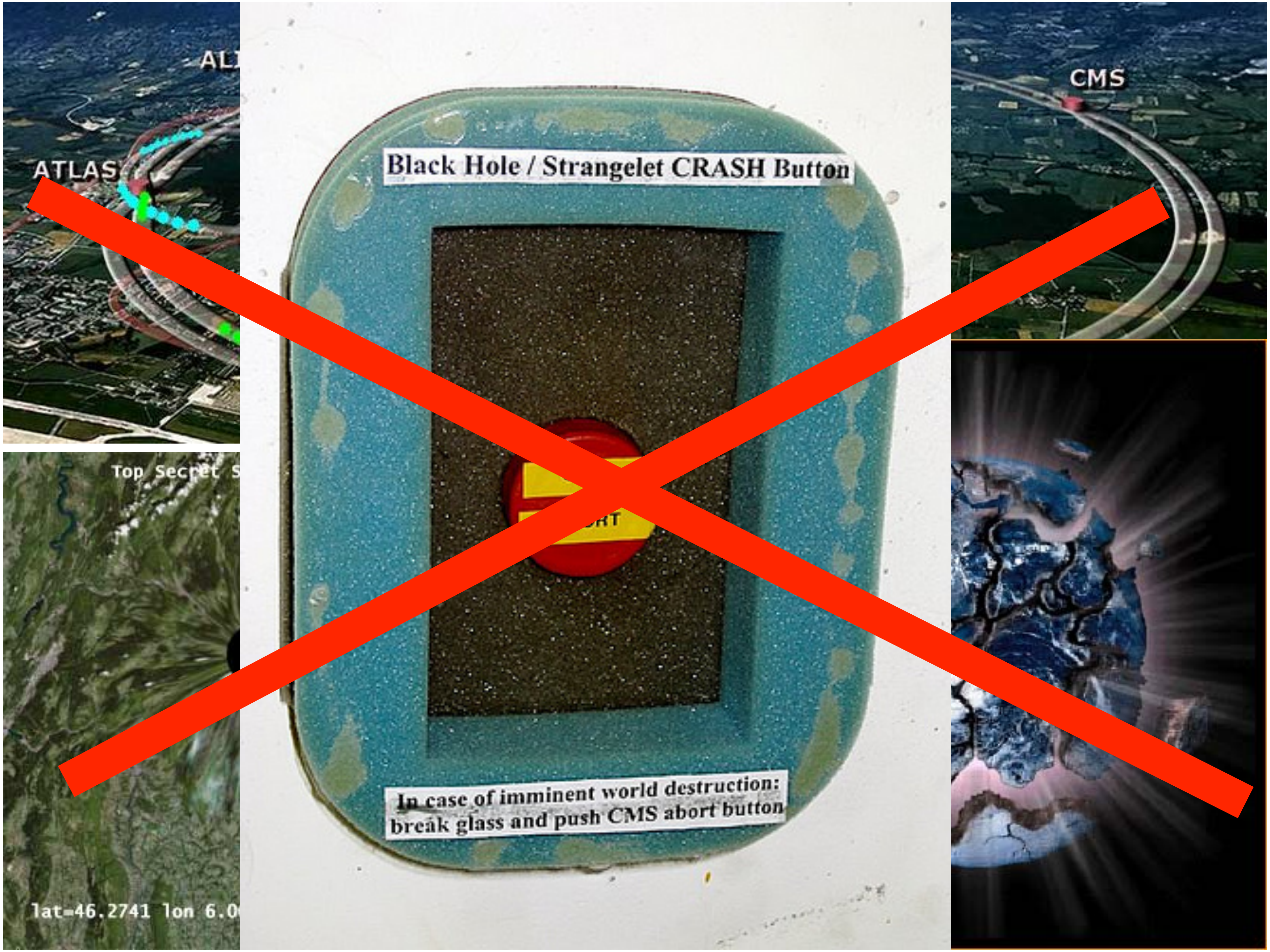
A 2011 Z boson event

… but now with 10 other collisions recorded at the same time!

Dealing with this 'pile-up' is a real headache, but can be done by tracing particles back to their different vertices …

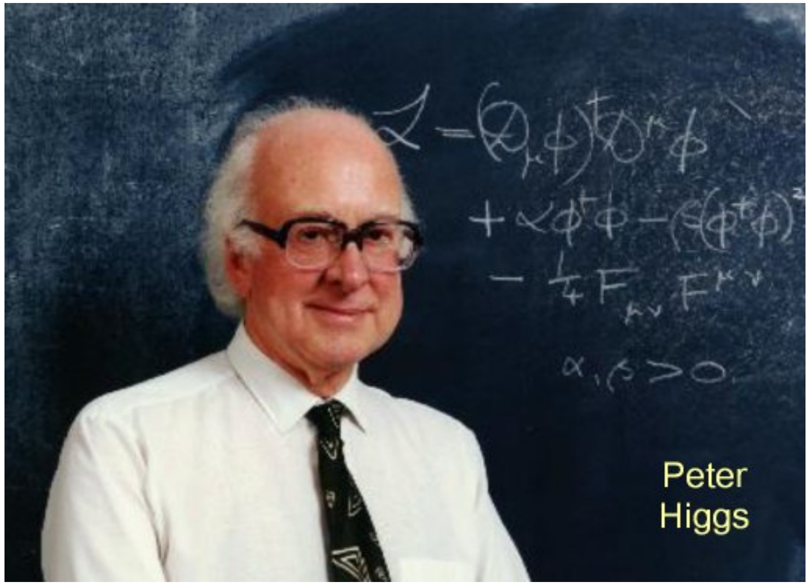
What might LHC discover?




ATLAS
Black Hole / Strangelet CRASH Button
In case of imminent world destruction:
break glass and push CMS abort button
CMS
Top Secret
lat=46.2741

What might the LHC Discover?...

Biggest open problem is how particles acquire mass &
why some are heavier than others

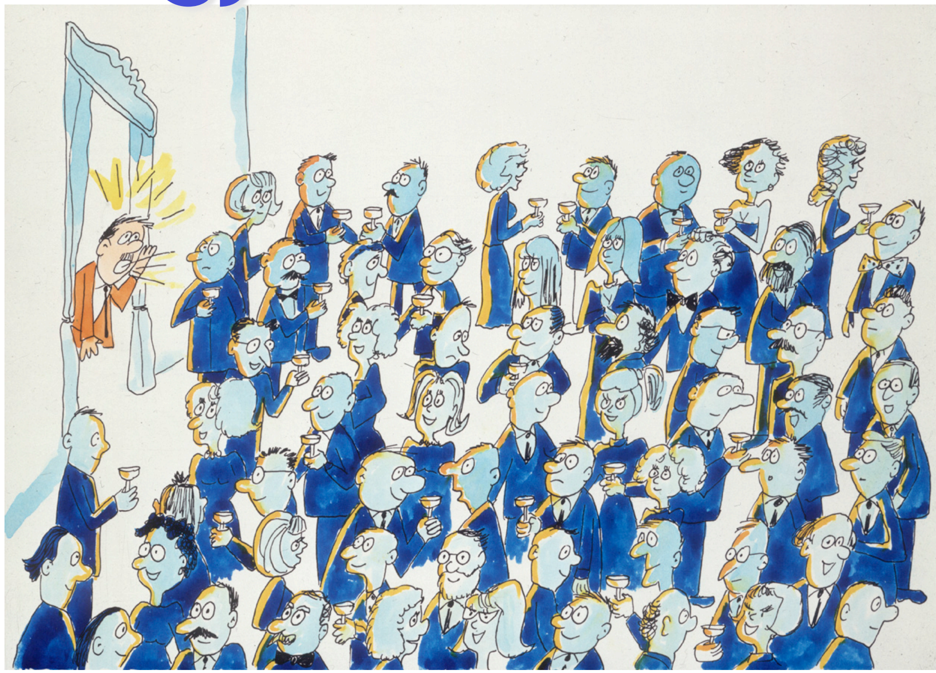


In the mid 1960s, British physicist Peter Higgs came up with a theory

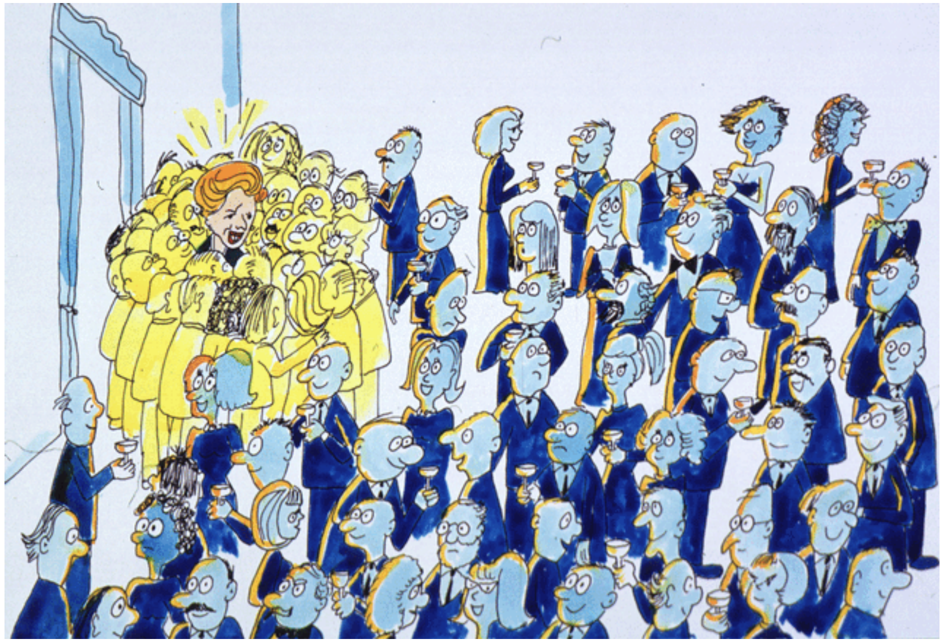
A new heavy particle, the Higgs Boson `grabs hold of' particles to slow them down

Particles which 'feel' this Higgs boson field gain mass...
... Light particles don't feel it strongly, heavy particles do.

A Higgs Analogy



What happens when a Mr Nobody and a Mrs Thatcher try to walk quickly through a room full of Conservative party workers?...



... so all we need to do is go and find it ...

How a Higgs boson event might look in ATLAS

In this event, a cluster of particles was produced going downward,

and a Higgs was produced going upward but decayed almost instantly.

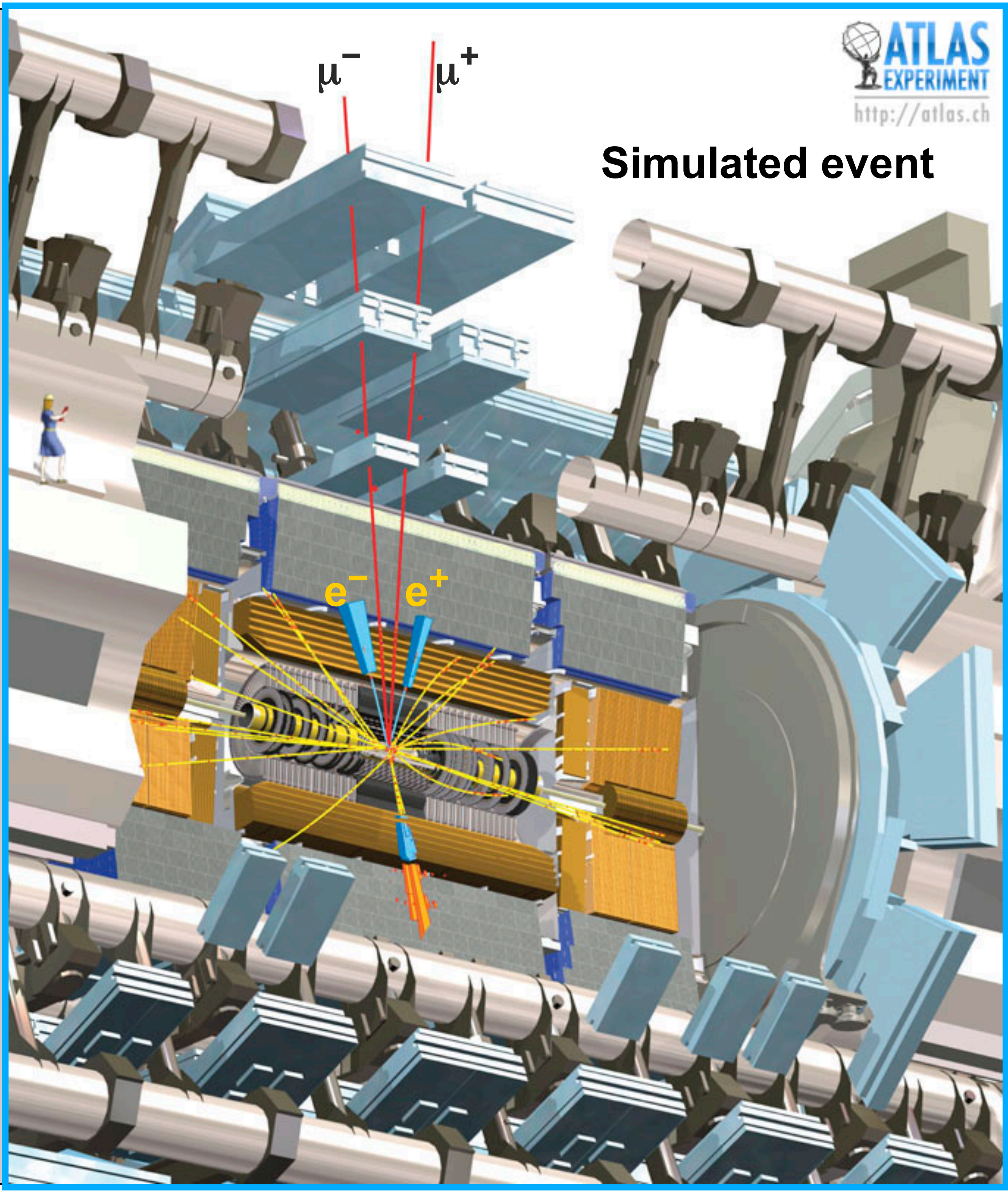
$H \rightarrow Z + Z$

$Z \rightarrow e^- + e^+$

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

1 billion events per second

1 Higgs produced every 10 seconds!



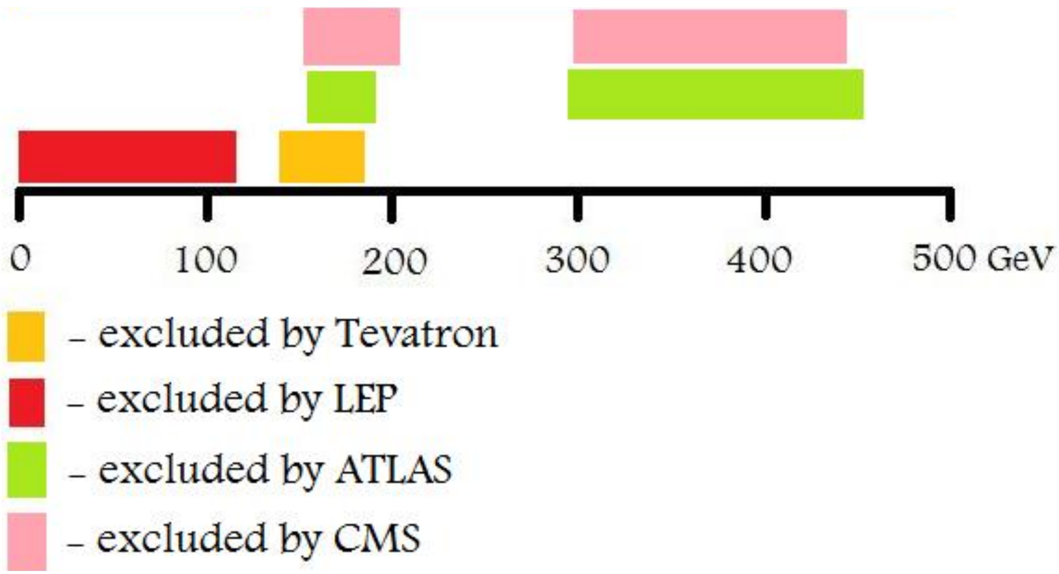
What can we say about the Higgs Boson?

~~It's like looking for a needle in a haystack~~

~~It's like looking for a needle in 10000 haystacks~~

It's like looking for a piece of hay in 10000 haystacks

... we're running out of hay ...

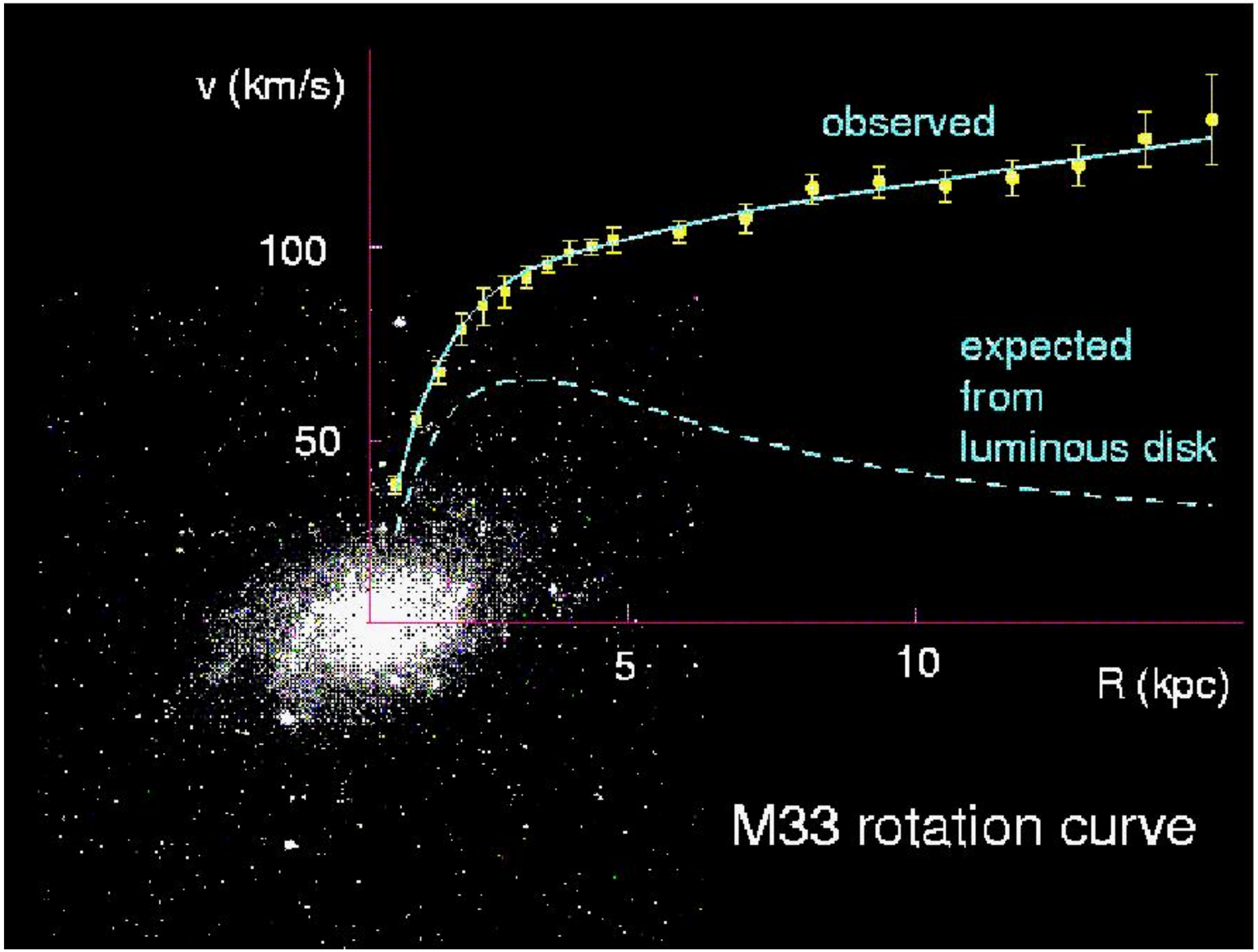


If the Higgs boson exists, its mass is most likely to be between about 115 GeV/c^2 and 140 GeV/c^2

If it doesn't exist, we need a whole new theory!

We expect to know by the end of 2012, one way or another!

A Connection to the Universe

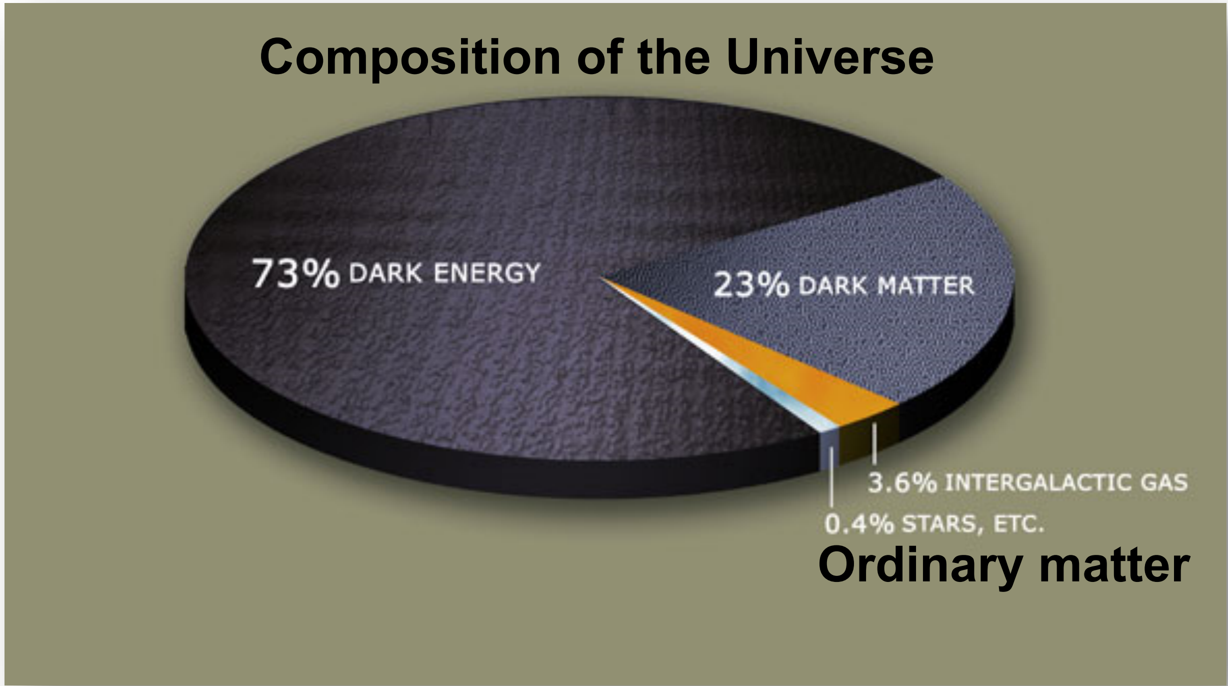


Looking at the relative rotation and gravitational attraction deep in the universe, either …

1) Einstien’s laws of gravity are wrong or …
2) There is much more “stuff” out there than we can see

There must be more than just Matter and Antimatter

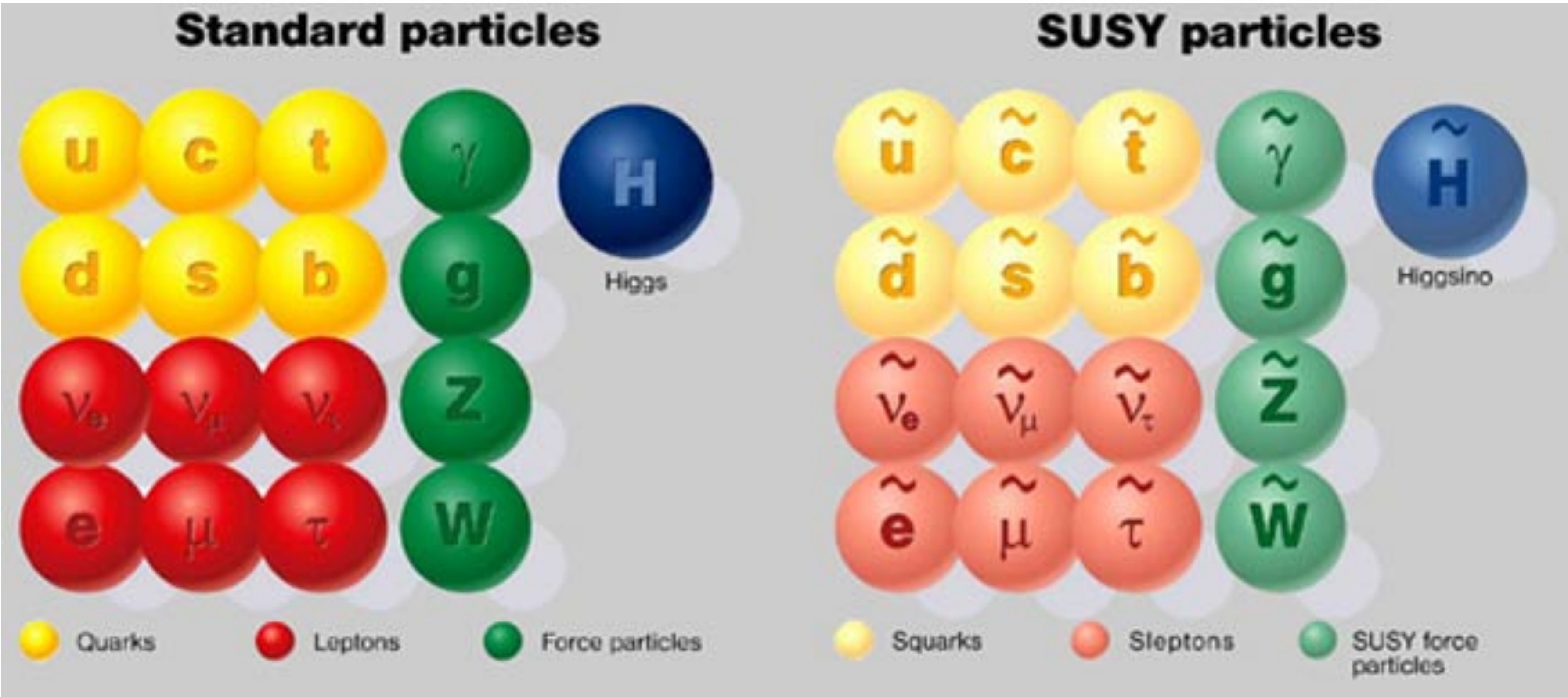
Looking at our Universe we see much more than ordinary matter (or antimatter)



The dark side of the universe…

If dark matter is made up of unknown elementary particles, they could be discovered at the LHC. e.g. Supersymmetry …

Supersymmetry and LHC Data

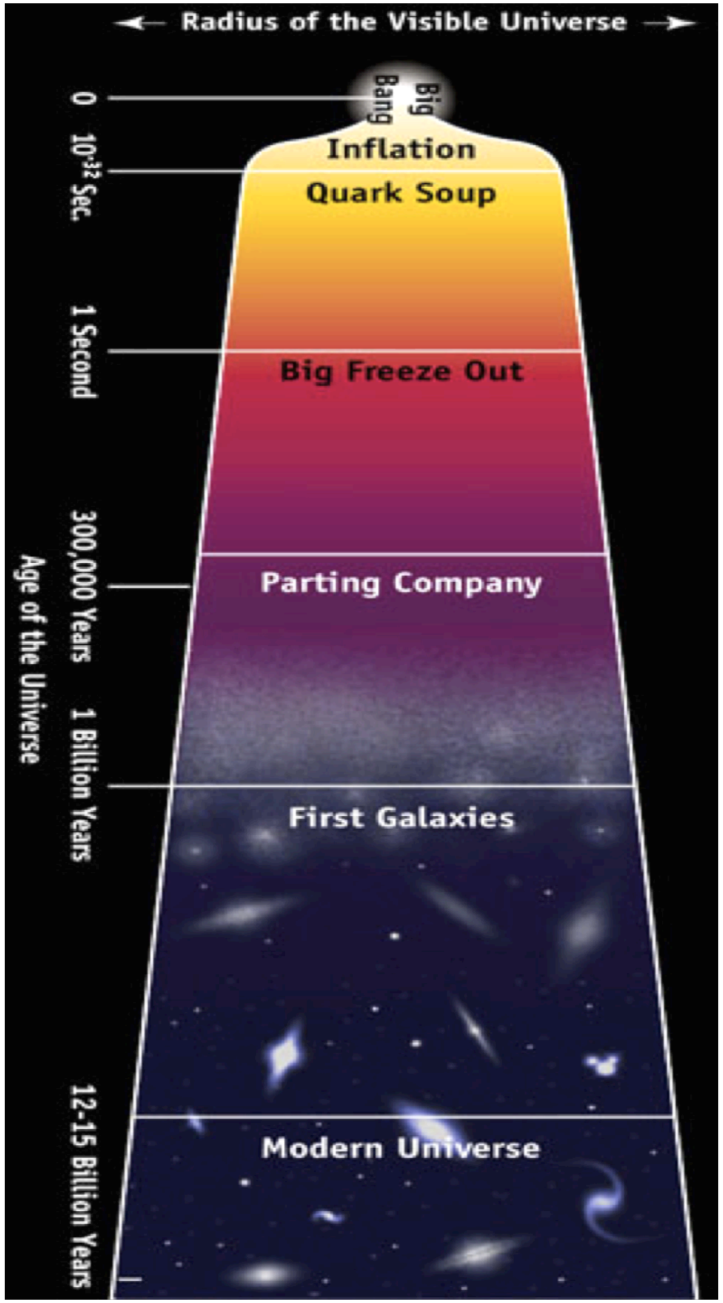


SUSY predicts that every known particle has a supersymmetric partner, differing in spin and mass.

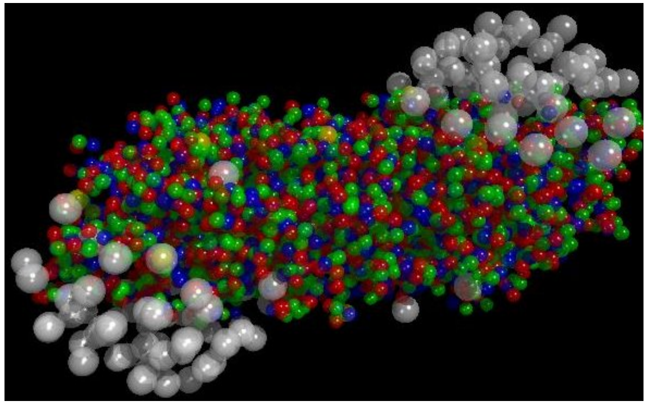
LHC is most likely to see the lighter ones (s-top?) first

… simplest version of SUSY ruled out by 2011 LHC data? …

ALICE and the Quark Gluon Plasma



ALICE experiment aims to study collisions between pairs of lead nuclei!



… this should recreate a state of matter in which hadrons 'dissolve' to produce a soup of unbound quarks and gluons (a '<u>Quark-Gluon Plasma</u>')

… recreating conditions that last existed around 10^{-6} seconds after the big bang

… when the temperature of the universe was ~10^{13} °C!

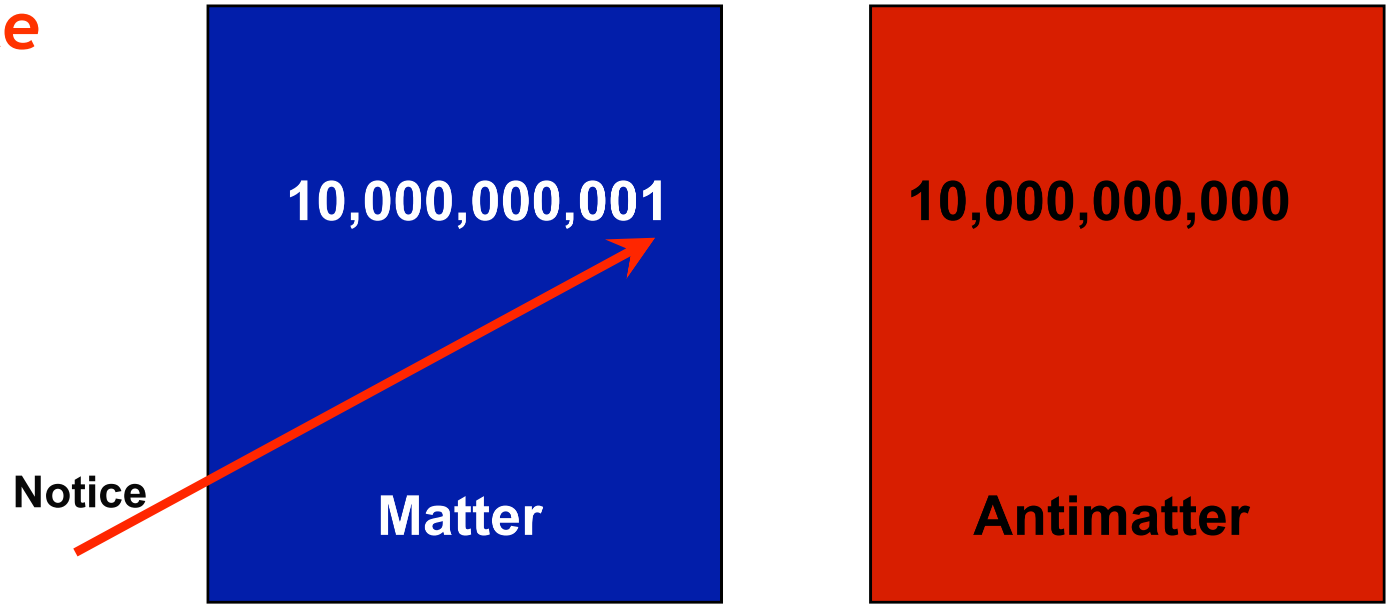
LHCb & the Matter/Antimatter Puzzle.

… if the big bang gave us equal amounts of matter and antimatter, where did all the antimatter go?…

The LHCb experiment is studying tiny differences between the lifetimes of beauty quarks and beauty antiquarks

… so a possible answer …

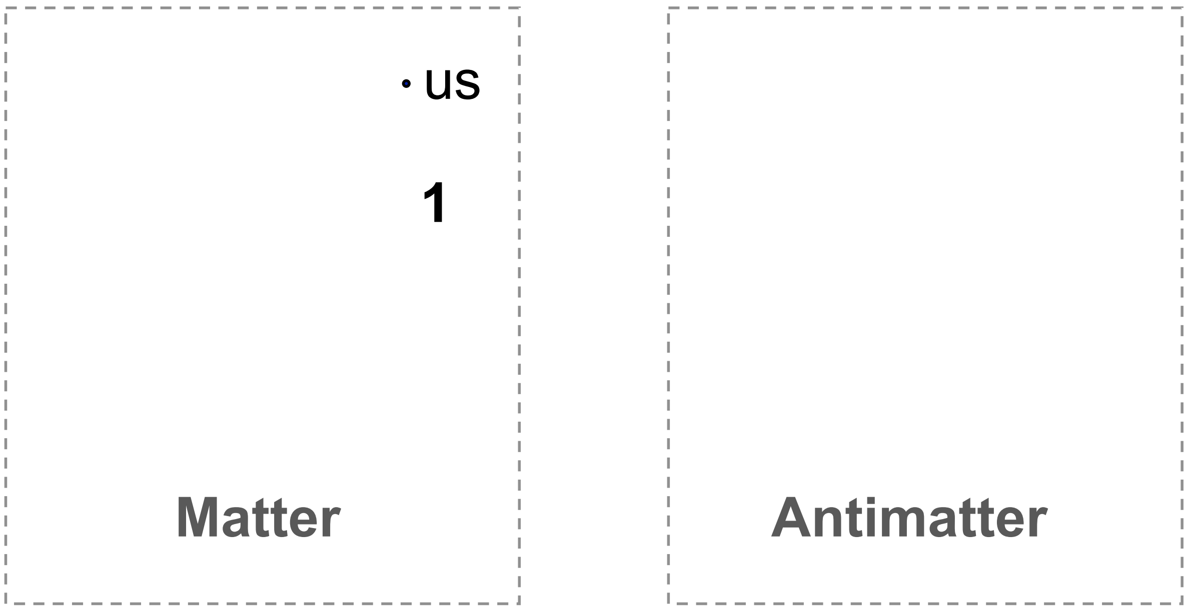
sometime just after the big bang …



Where is all the Antimatter?

… a great annihilation then took place …

… leaving only a "tiny" part of the matter … us!

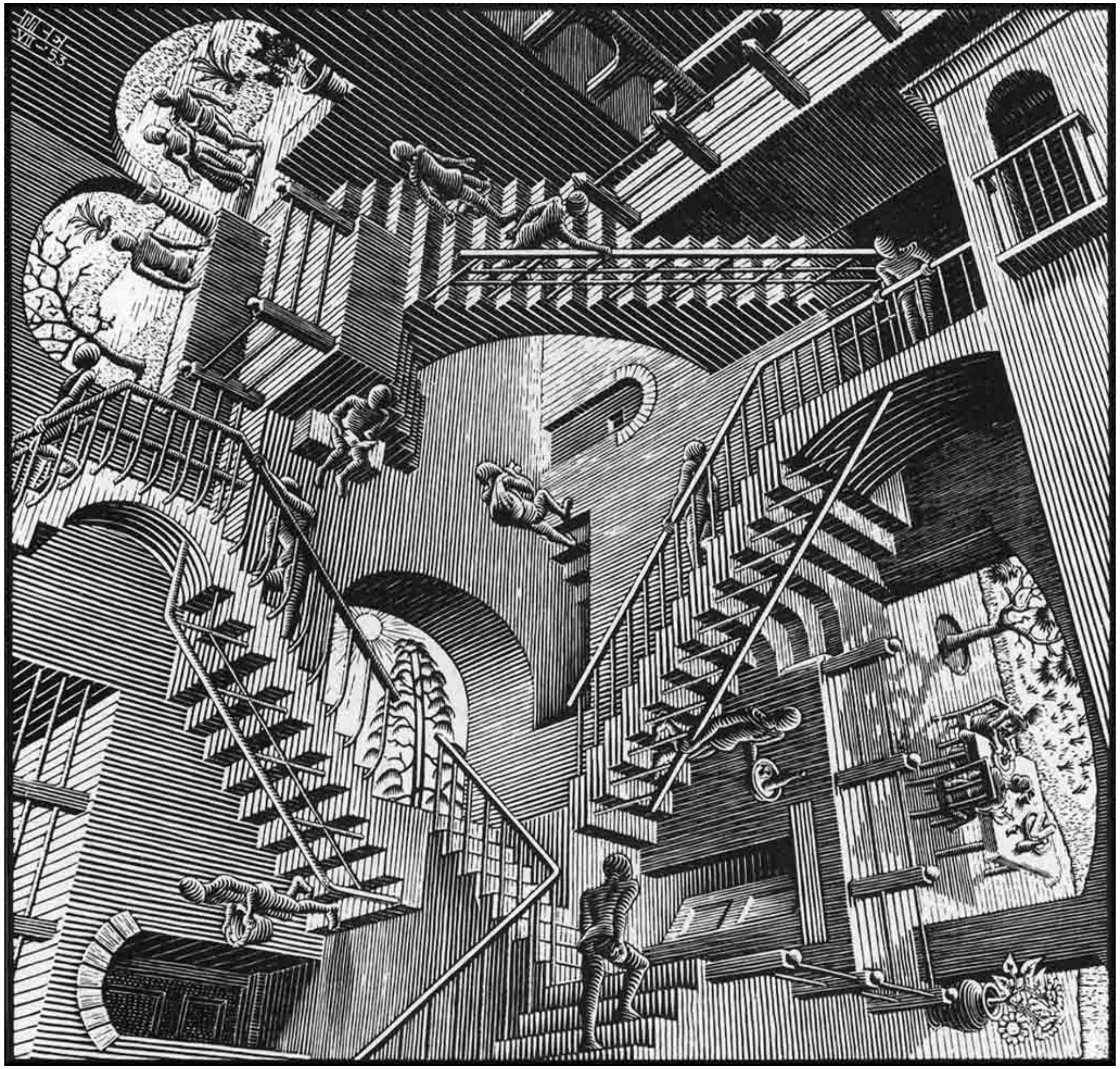


Are there New Unknown Dimensions?

- Could explain why gravity is so extremely weak?…

- Maybe it is really stronger, but operates in more dimensions and we feel only its relics?

- … could give rise to the production of mini black holes at the LHC

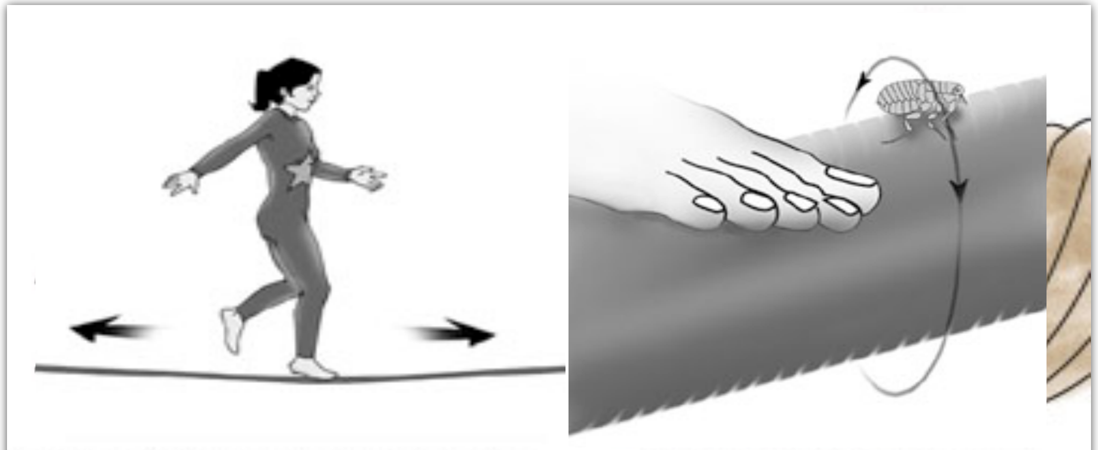


- it's OK …they're quite safe ☺

How can there be extra dimensions?

- Think about an acrobat and a flea on a tight rope.
- The acrobat can move forward & backward along rope.
- … but the flea can also move sideways around the rope.

If the flea keeps walking to one side, it goes around the rope and winds up where it started.



An acrobat can only move in one dimension along a rope..

...but a flea can move in two dimensions.

Maybe there could be inperceptible extra dimensions curled up like this by gravity?

… there are many other possibilities for what might be seen at the LHC … including lots that nobody thought of yet!

The Future?

- Will we see a deeper structure to the quarks?

- Will we understand why there are three families of quarks?

- Will we see the Higgs boson?

- Will we see Supersymmetry, Extra Dimensions, or something completely unexpected!

… it's early days. Currently → half design beam energy
→ 1/1000 of planned collisions

- We should have an answer to the Higgs boson question in the next 18 months … but most new physics is extremely rare

- The LHC will run for 15-20 years … **WATCH THIS SPACE!**