

# An Introduction to Particle Physics & Accelerators [or Stuff: What is it?]

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UNIVERSITY OF  
BIRMINGHAM

**Physics & Astronomy Summer School  
14 July 2011**

# Late 19<sup>th</sup> Century: Atoms as nature's basic building blocks

1 <b>H</b> Hydrogen 1.00794																	2 <b>He</b> Helium 4.003
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.012182											5 <b>B</b> Boron 10.811	6 <b>C</b> Carbon 12.0107	7 <b>N</b> Nitrogen 14.00674	8 <b>O</b> Oxygen 15.9994	9 <b>F</b> Fluorine 18.9984032	10 <b>Ne</b> Neon 20.1797
11 <b>Na</b> Sodium 22.989770	12 <b>Mg</b> Magnesium 24.3050											13 <b>Al</b> Aluminum 26.981538	14 <b>Si</b> Silicon 28.0855	15 <b>P</b> Phosphorus 30.973761	16 <b>S</b> Sulfur 32.066	17 <b>Cl</b> Chlorine 35.4527	18 <b>Ar</b> Argon 39.948
19 <b>K</b> Potassium 39.0983	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.955910	22 <b>Ti</b> Titanium 47.867	23 <b>V</b> Vanadium 50.9415	24 <b>Cr</b> Chromium 51.9961	25 <b>Mn</b> Manganese 54.938049	26 <b>Fe</b> Iron 55.845	27 <b>Co</b> Cobalt 58.933200	28 <b>Ni</b> Nickel 58.6934	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.39	31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.61	33 <b>As</b> Arsenic 74.92160	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.80
37 <b>Rb</b> Rubidium 85.4678	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.90585	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.90638	42 <b>Mo</b> Molybdenum 95.94	43 <b>Tc</b> Technetium (98)	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.90550	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.8682	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.710	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.60	53 <b>I</b> Iodine 126.90447	54 <b>Xe</b> Xenon 131.29
55 <b>Cs</b> Cesium 132.90545	56 <b>Ba</b> Barium 137.327	57 <b>La</b> Lanthanum 138.9055	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.9479	74 <b>W</b> Tungsten 183.84	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.217	78 <b>Pt</b> Platinum 195.078	79 <b>Au</b> Gold 196.96655	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.3833	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98038	84 <b>Po</b> Polonium (209)	85 <b>At</b> Astatine (210)	86 <b>Rn</b> Radon (222)
87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium (226)	89 <b>Ac</b> Actinium (227)	104 <b>Rf</b> Rutherfordium (261)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (263)	107 <b>Bh</b> Bohrium (262)	108 <b>Hs</b> Hassium (265)	109 <b>Mt</b> Meitnerium (266)	110 <b>Ds</b> Darmstadtium (269)	111 <b>Rg</b> Roentgenium (272)	112 <b>Cn</b> Copernicium (277)	113	114				

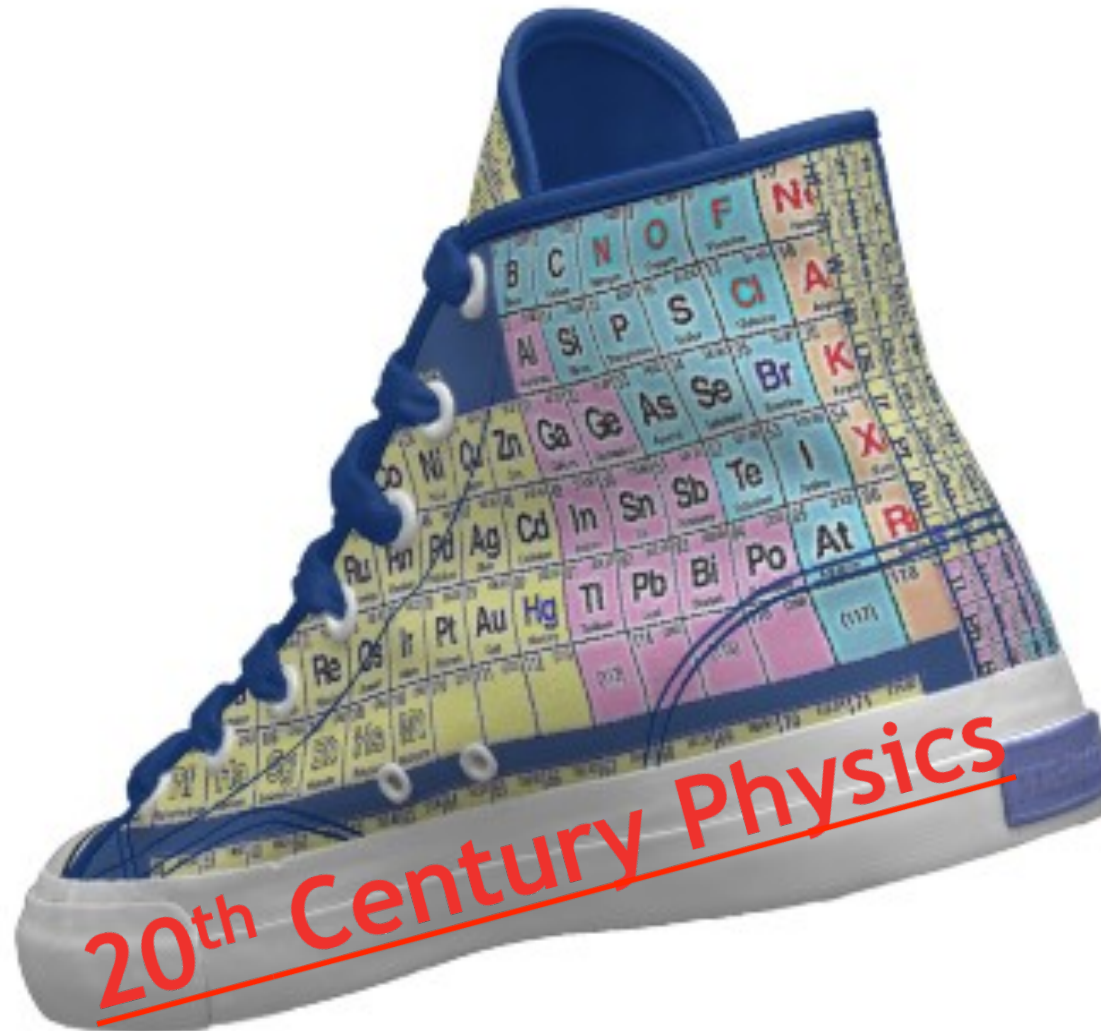
58 <b>Ce</b> Cerium 140.116	59 <b>Pr</b> Praseodymium 140.90765	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.964	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.92534	66 <b>Dy</b> Dysprosium 162.50	67 <b>Ho</b> Holmium 164.93032	68 <b>Er</b> Erbium 167.26	69 <b>Tm</b> Thulium 168.93421	70 <b>Yb</b> Ytterbium 173.04	71 <b>Lu</b> Lutetium 174.967
90 <b>Th</b> Thorium 232.0381	91 <b>Pa</b> Protactinium 231.03588	92 <b>U</b> Uranium 238.0289	93 <b>Np</b> Neptunium (237)	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 <b>Cf</b> Californium (251)	99 <b>Es</b> Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 <b>Md</b> Mendelevium (258)	102 <b>No</b> Nobelium (259)	103 <b>Lr</b> Lawrencium (262)

"There is nothing new to be discovered in physics now,  
All that remains is more and more precise measurement."  
Lord Kelvin, 1900

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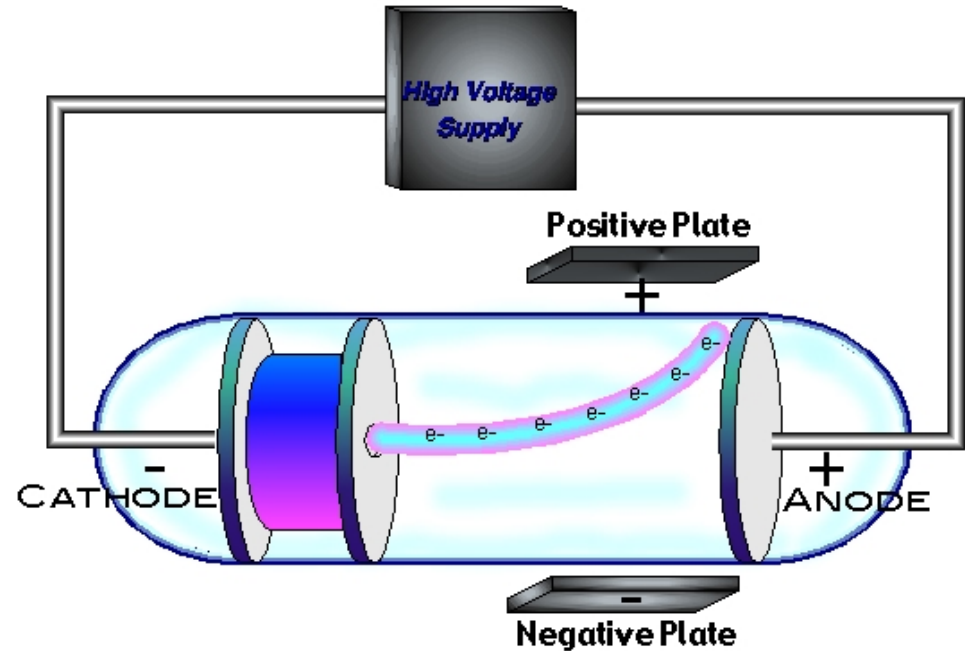
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A much deeper (and simpler) structure has been revealed in collisions of very high energy particles at accelerators

# Cathode Ray Tubes

High Voltage passed  
across low pressure gas

Mysterious charged particles  
emitted from cathode



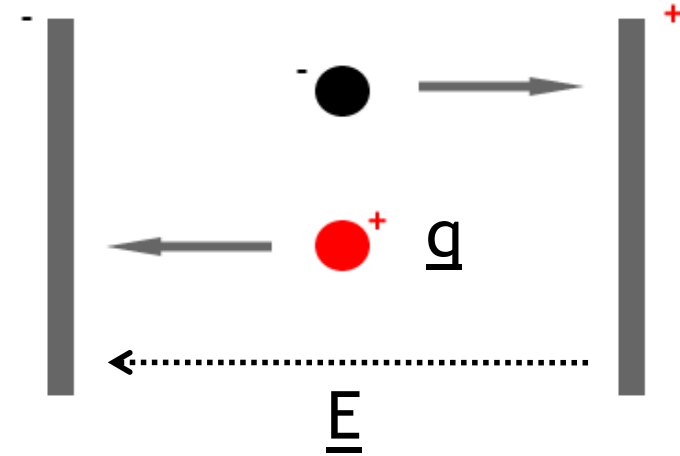
1897: JJ Thomson measured cathode ray mass from bending in electric field

... 1/1000<sup>th</sup> 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

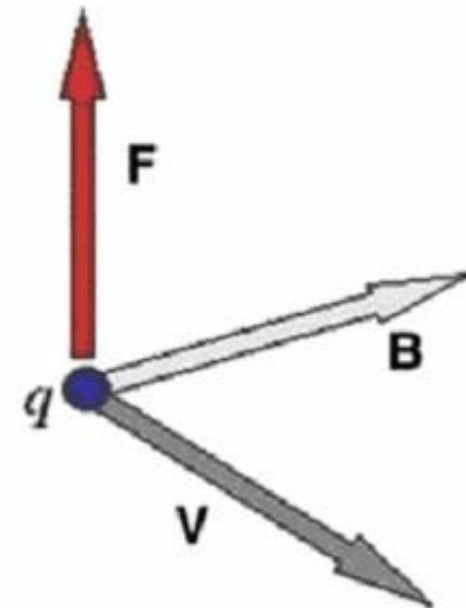
$$F = ma = qE$$



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!

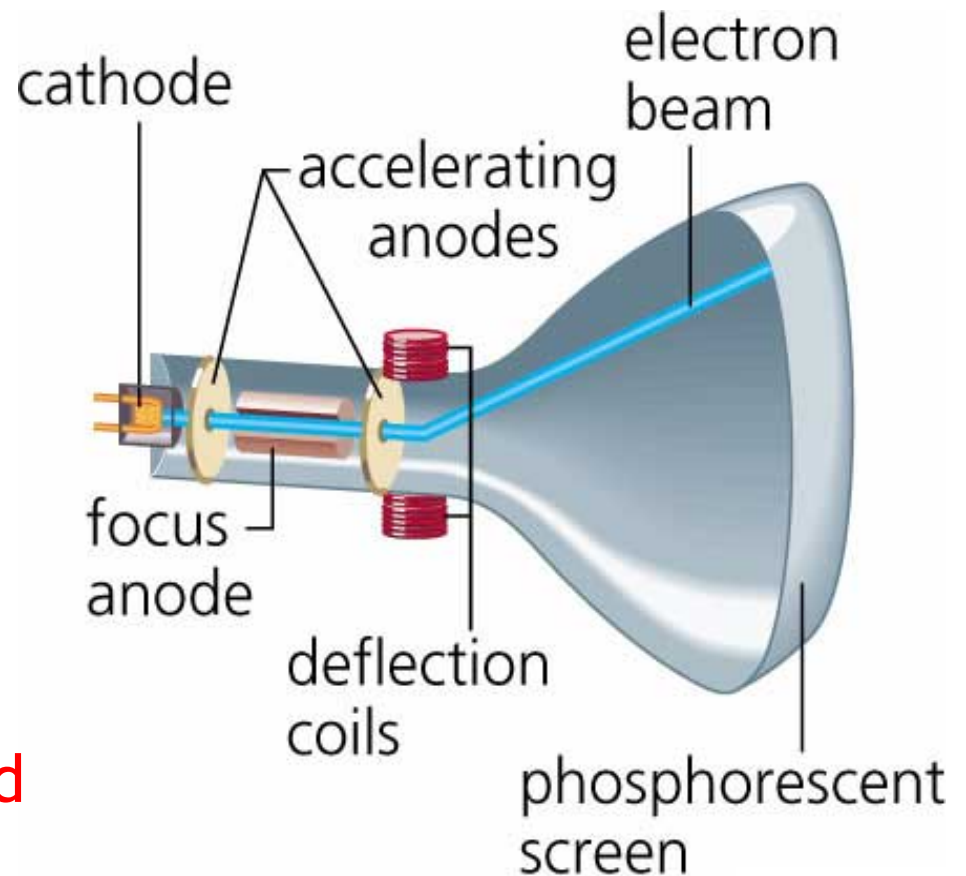
## A USEFUL UNIT

A particle of charge  $q$  accelerated through a potential difference

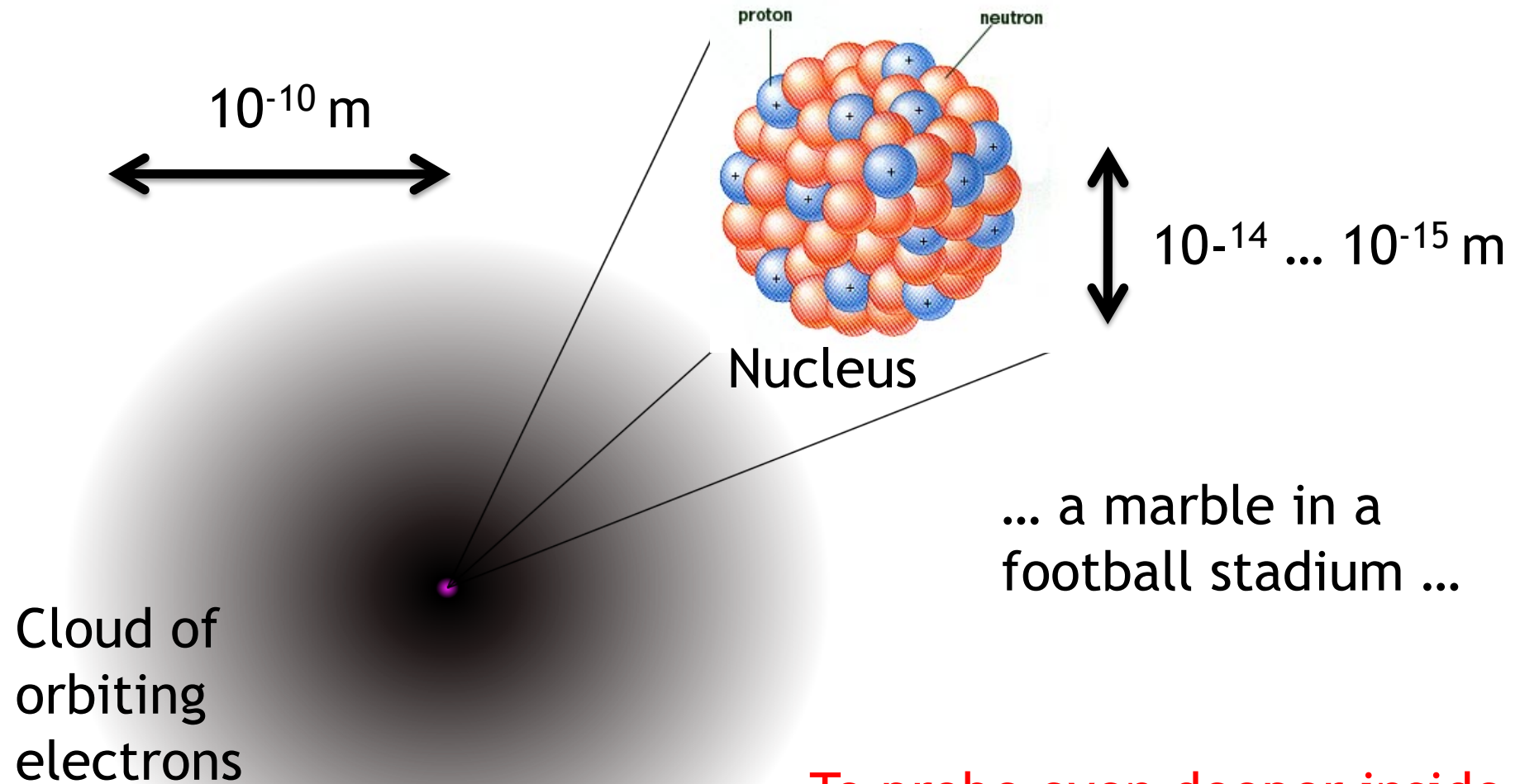
$V$  acquires a kinetic energy  $KE=qV$ .

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

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



# A Modern Picture of the Atom



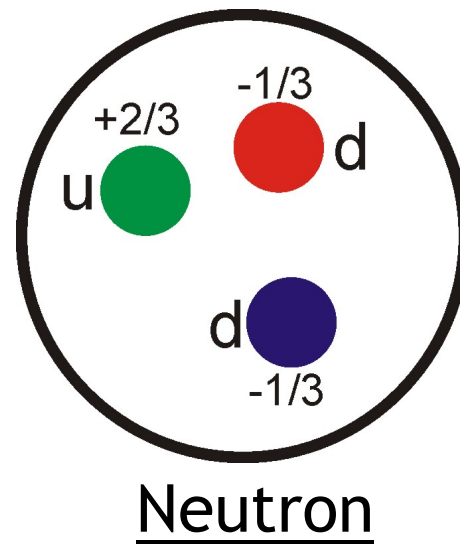
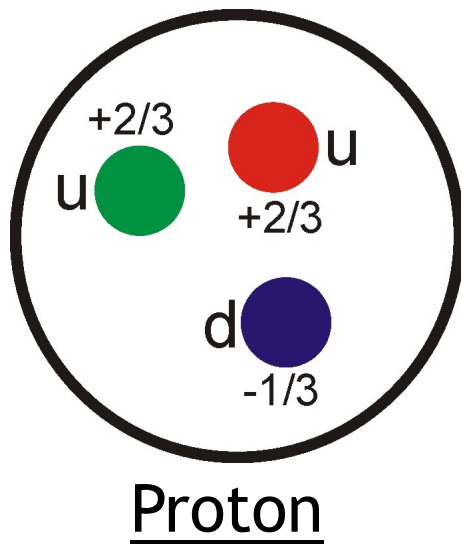
... a marble in a football stadium ...

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

# The Modern Picture of Protons and Neutrons

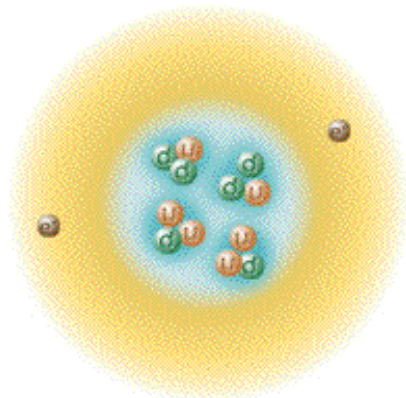
In 1969, an experiment using a 2-mile long 20 GeV electron accelerator showed that protons have structure → “quarks”

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

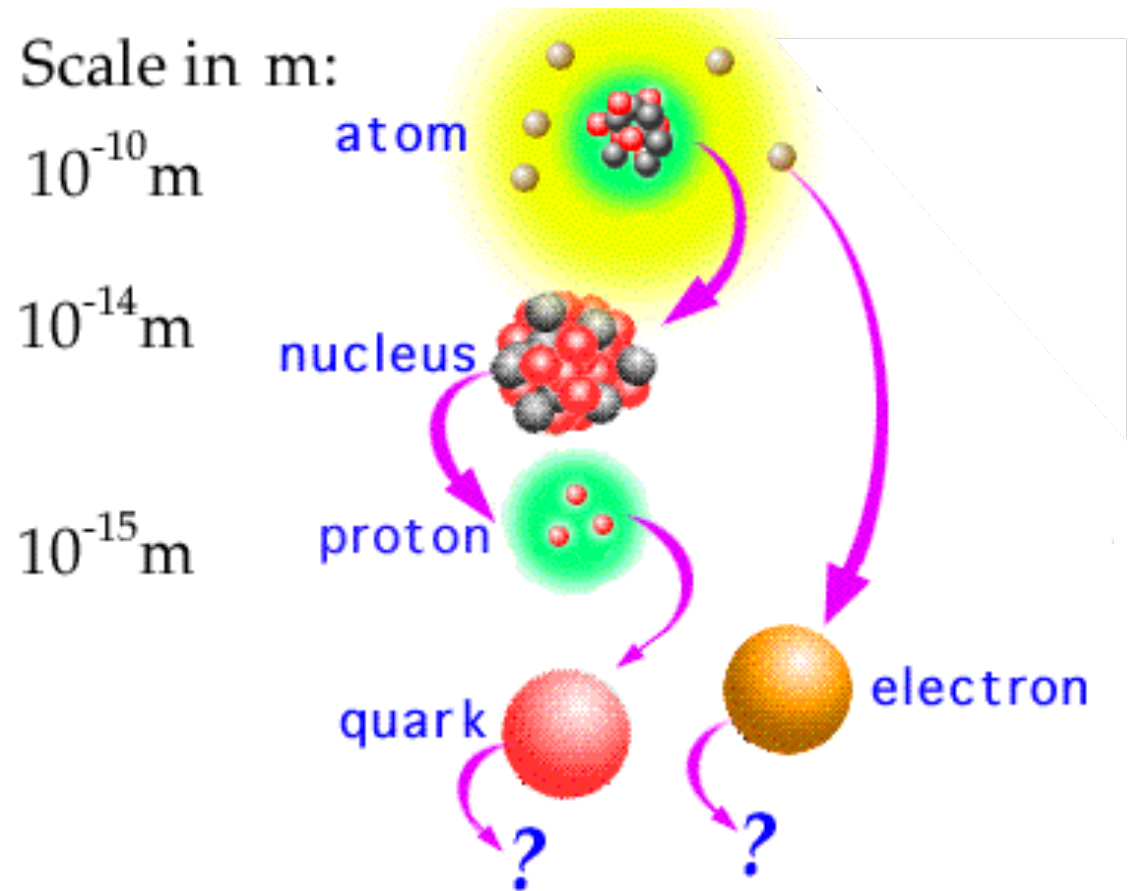


# So What is 'Stuff' Ultimately Made of?

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



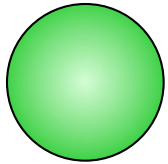
- Nuclei consist of protons and neutrons.
- The protons and neutrons are made of **quarks**.



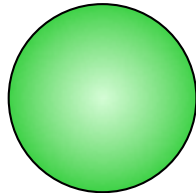
# ... A Nice Happy Family of Particles



**Up quark (u)**



**Down quark (d)**



**Electron (e<sup>-</sup>)**



**Electron neutrino (ν<sub>e</sub>)**



Mass ~ 0.003

~ 0.006

= 0.0005

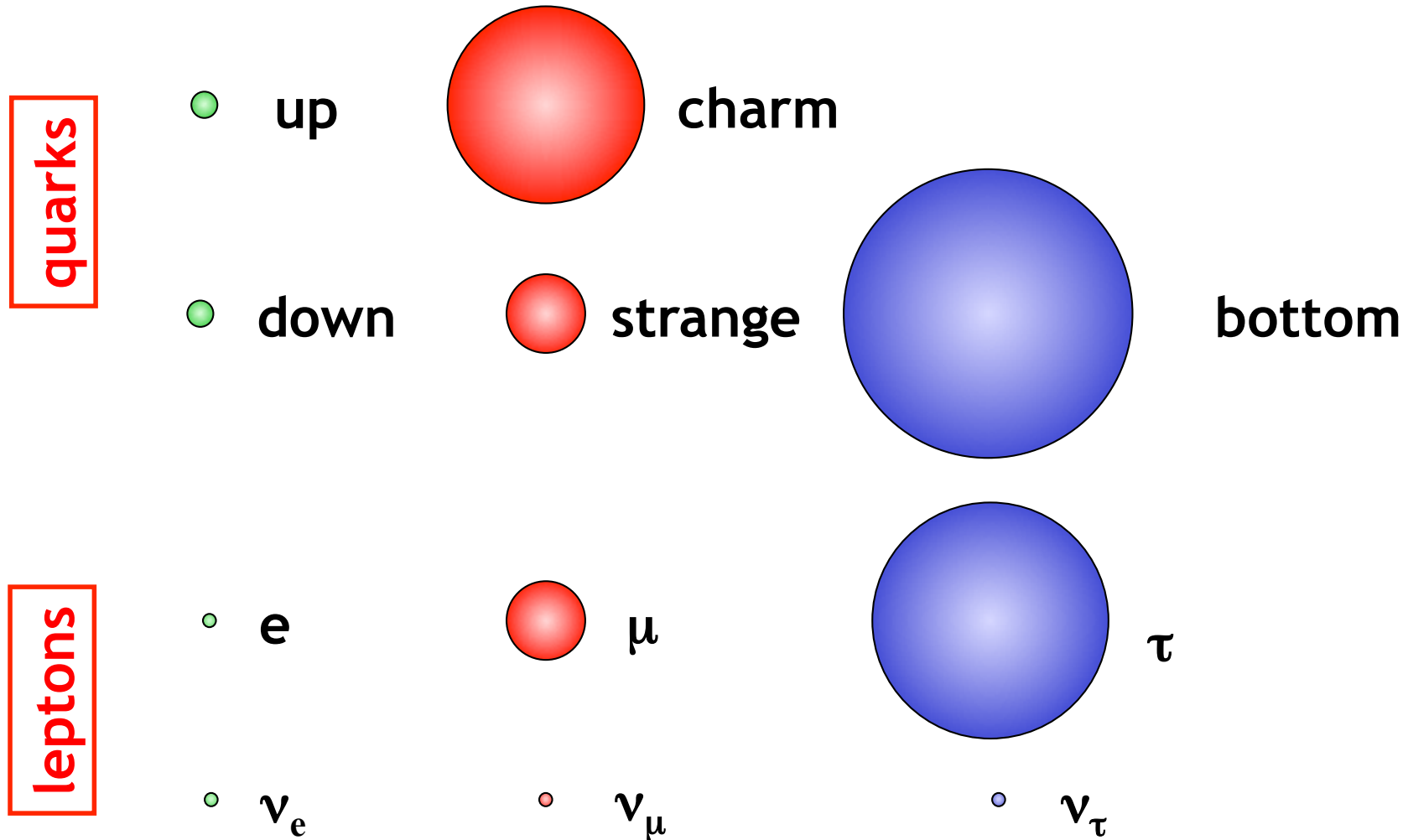
~ 10<sup>-8</sup> ?

(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?

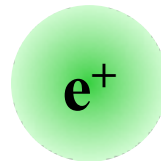
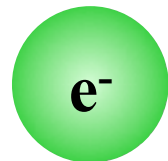
# What about Antimatter?

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.

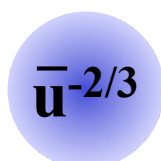


electron



positron

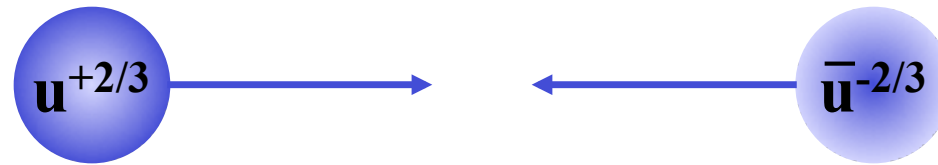
up quark



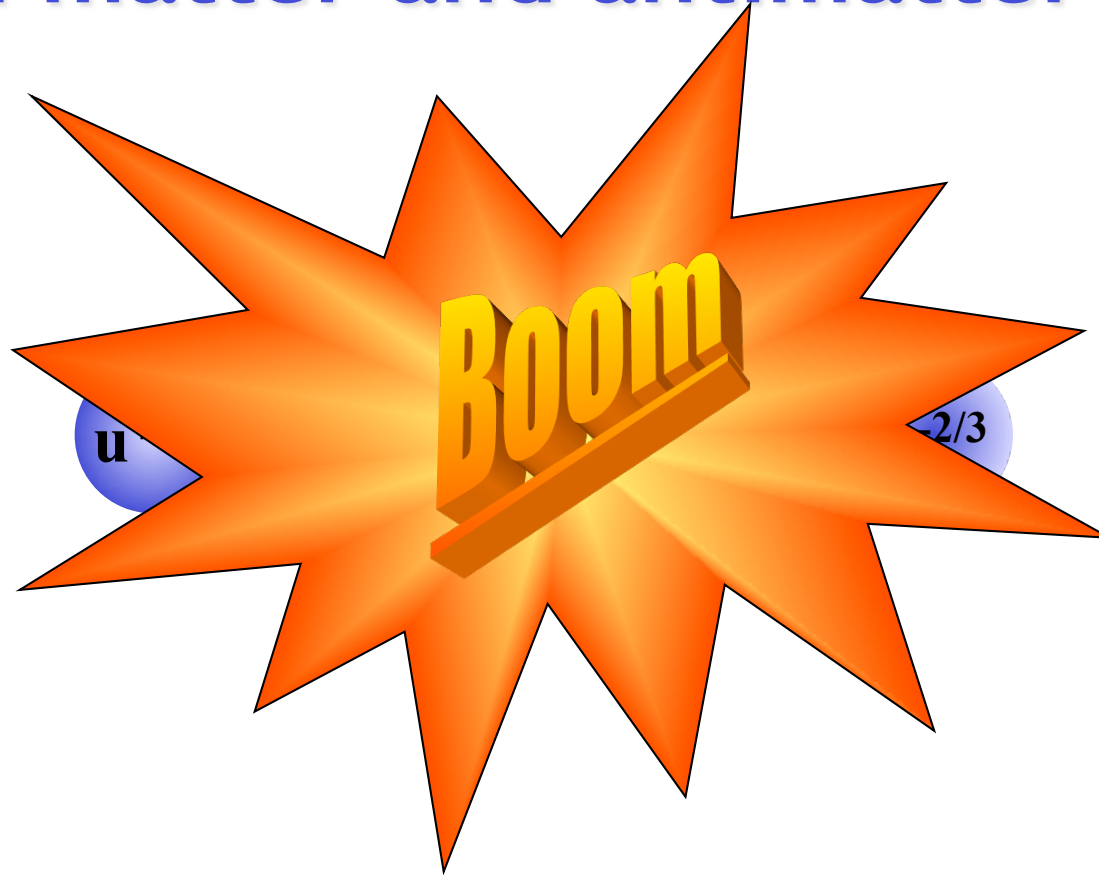
up anti-quark

etc etc ...

# When matter and antimatter meet ...



# When matter and antimatter meet ...




- If a particle and an antiparticle, each of mass  $m$ , collide, they annihilate, producing energy  $E = 2mc^2$
- 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**


$$F = \frac{1}{4\pi\epsilon_0} \frac{q_1 q_2}{r^2}$$

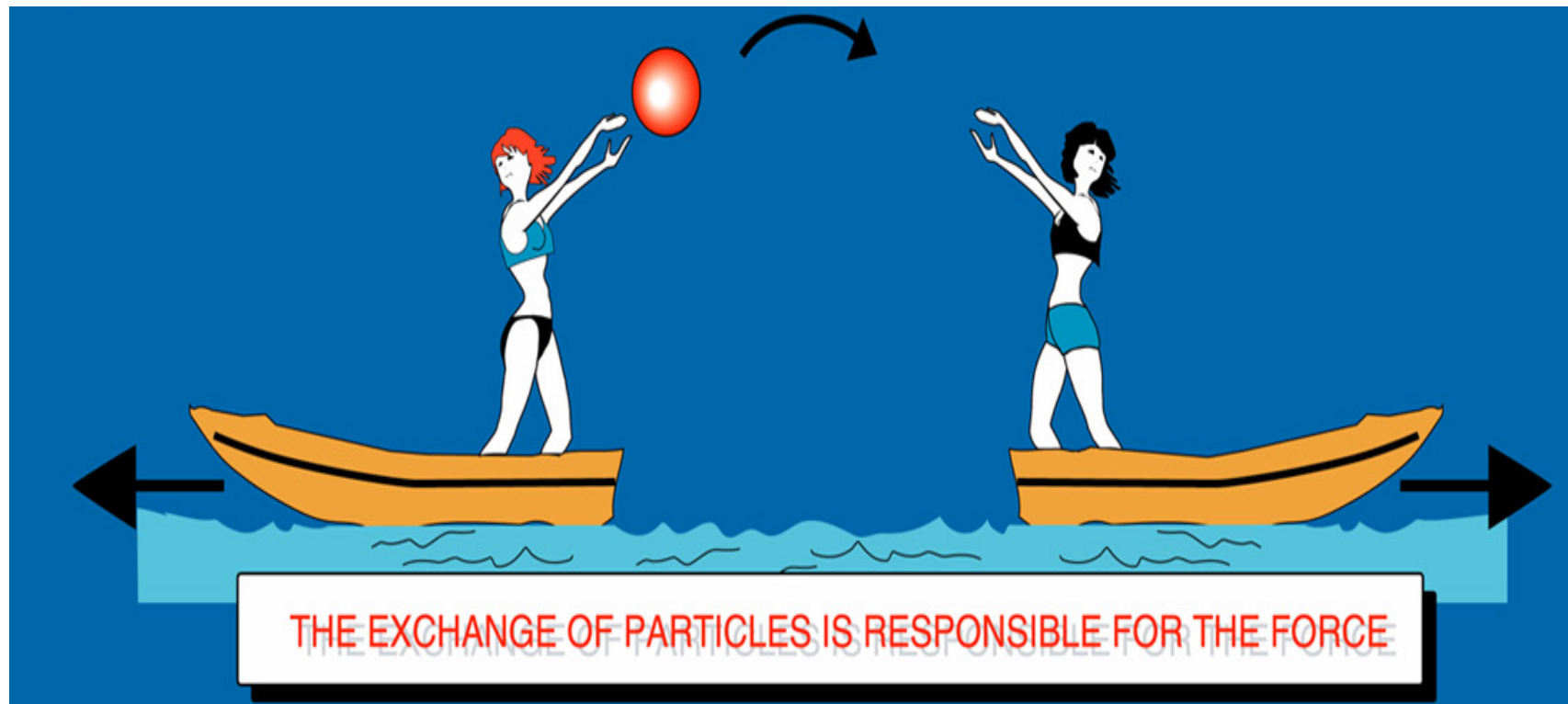
2) The **strong nuclear force** holds the quarks together in the protons and neutrons ... **so that they can't escape** ...


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

3) The **weak nuclear force** is responsible for nuclear  $\beta$  decay: close relative of electromagnetic force ... but **short range** ...

# The Particle Physics view of Forces

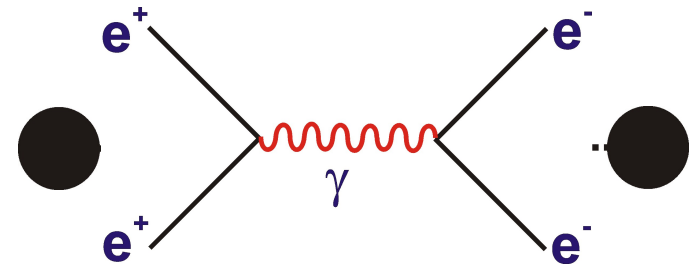
The microscopic view: forces also caused by particles ... being exchanged between the matter particles



# The Force Carriers

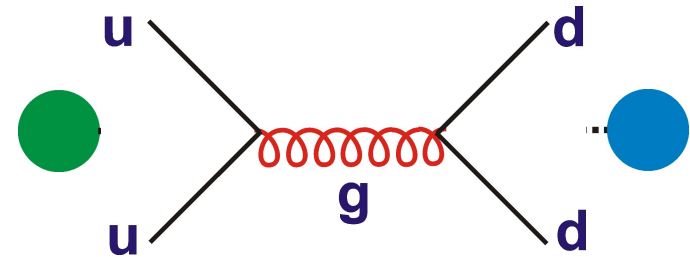
## 1) Electromagnetic force

PHOTON EXCHANGE



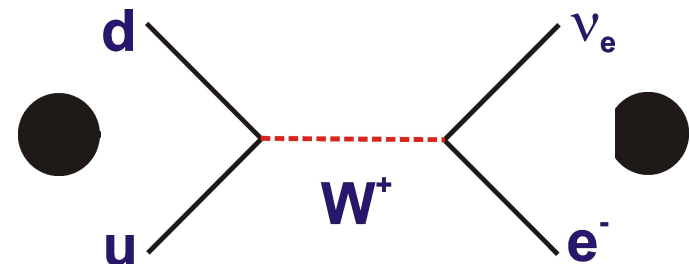
## 2) Strong nuclear force

GLUON EXCHANGE



## 3) Weak nuclear force

$Z^0$ ,  $W^+$ ,  $W^-$  EXCHANGE



Short range because  $W$  and  $Z$  bosons are HEAVY:

... 80-90 times heavier than a proton!

# → The present day ... on the Swiss French Border ...



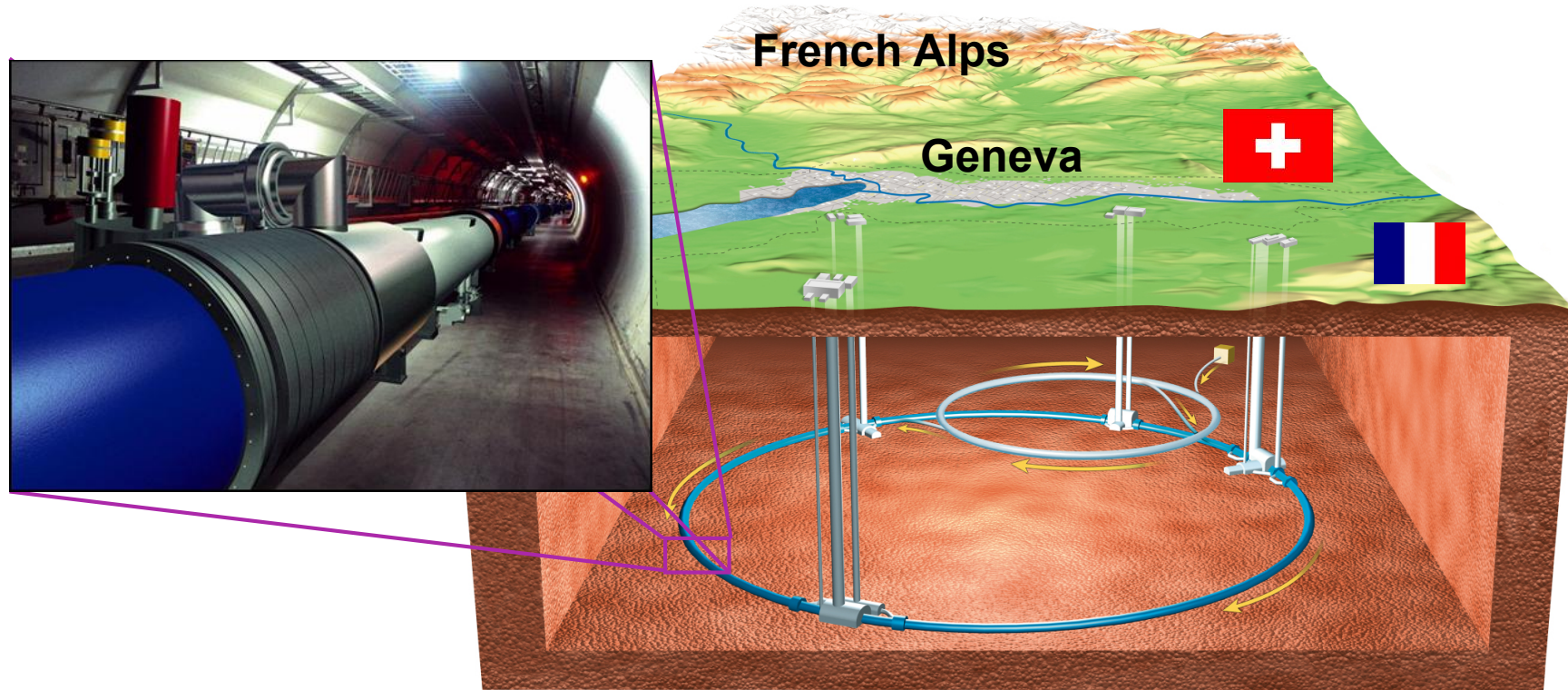
... near Lake Geneva,  
between the Alps and the Jura



... is the world's largest Physics Laboratory



... what CERN is currently doing ...

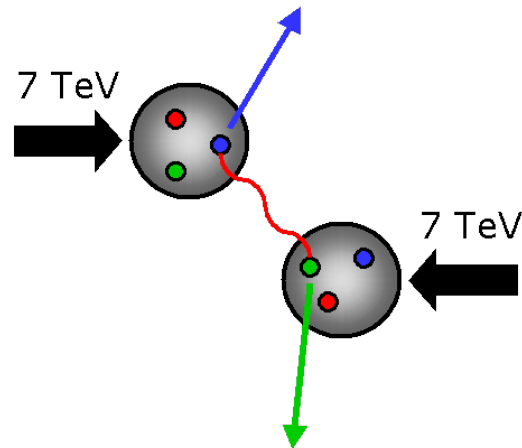


## The Large Hadron Collider (LHC)

100m underground ... in a 27km long tunnel...

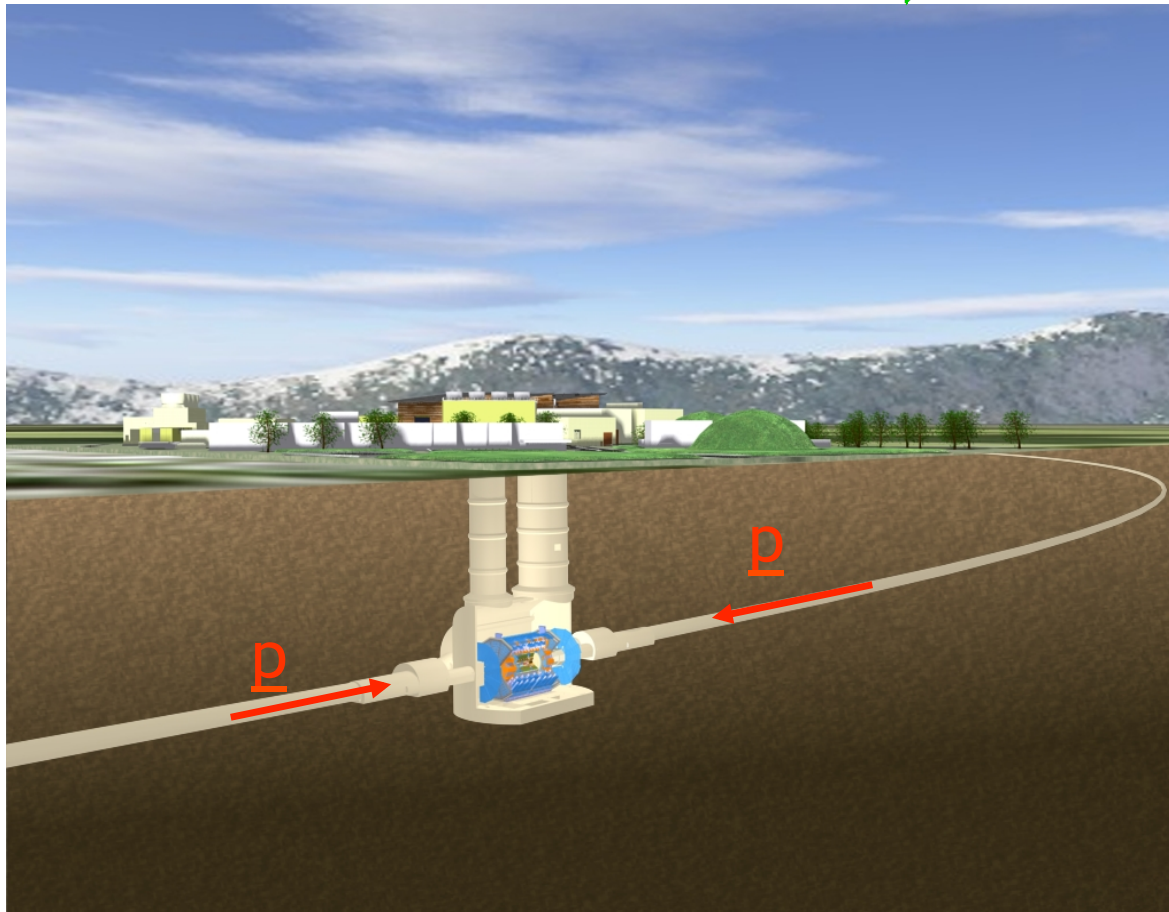
... accelerates protons to 0.9999999991 of the speed of light.

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



## The LHC Beams

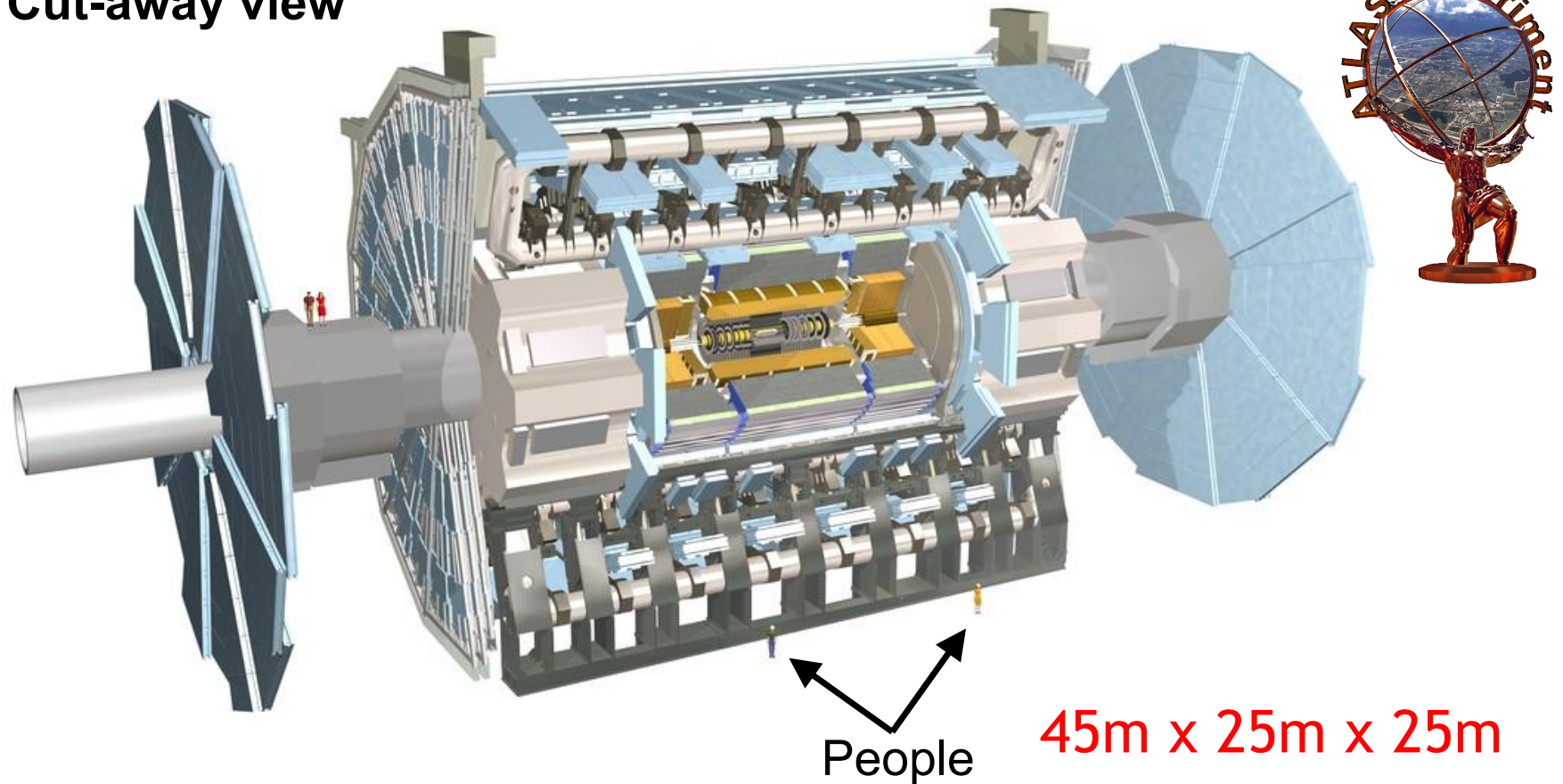
- Each proton goes round ring 11,000 times per Second.
- $10^{11}$  protons per bunch, with 40 million bunch crossings per second
- Total stored energy of 300 MJ ... equivalent to a family car at 100 mph
- Ring looks just 4m long to the protons!



# 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.

Cut-away view

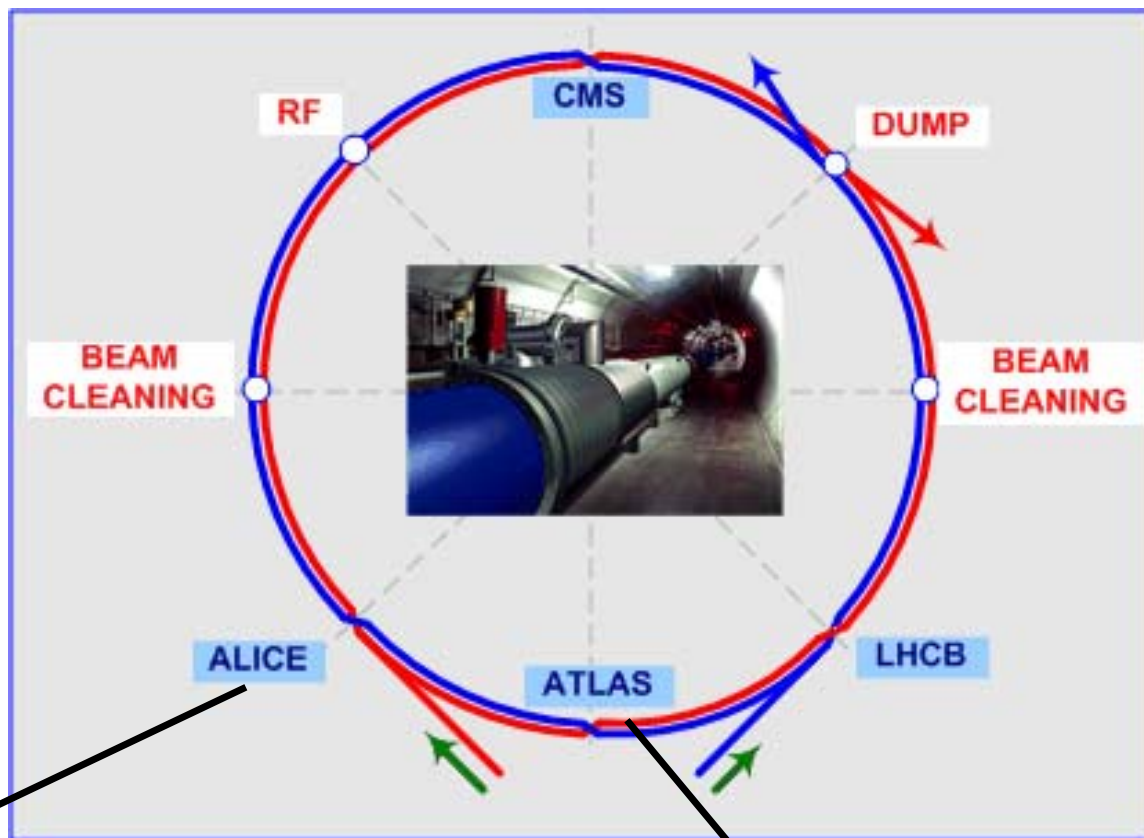


The scientific collaborations are as big as the detectors ...  
e.g. ATLAS involves ~3000 physicists from 173 institutes  
in 37 different countries



# Birmingham & the LHC

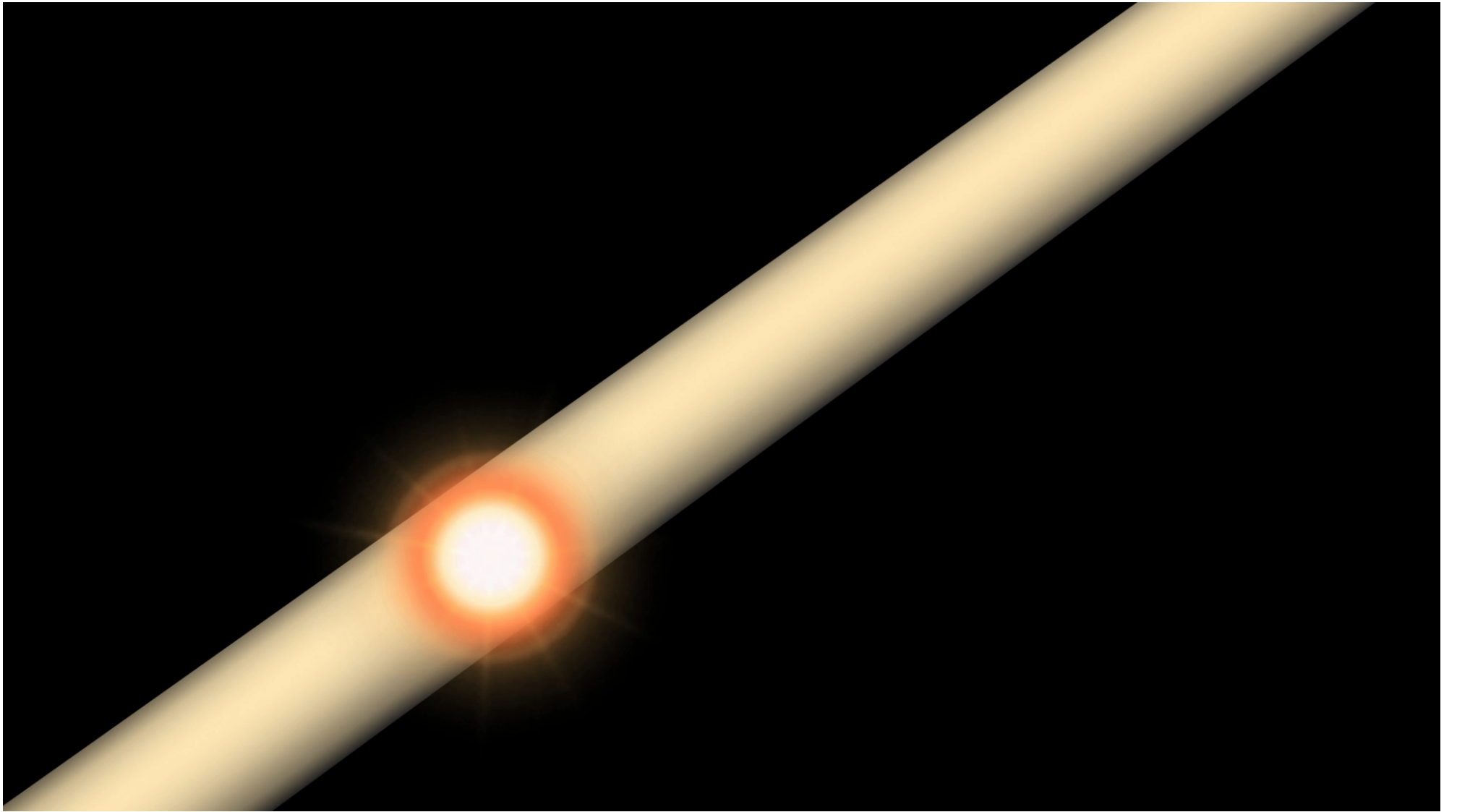
Birmingham has large groups, playing important roles in three of the four LHC experiments, ALICE, ATLAS & LHCb



David Evans,  
UK ALICE  
Spokesman

Dave Charlton,  
ATLAS  
Deputy  
Spokesman



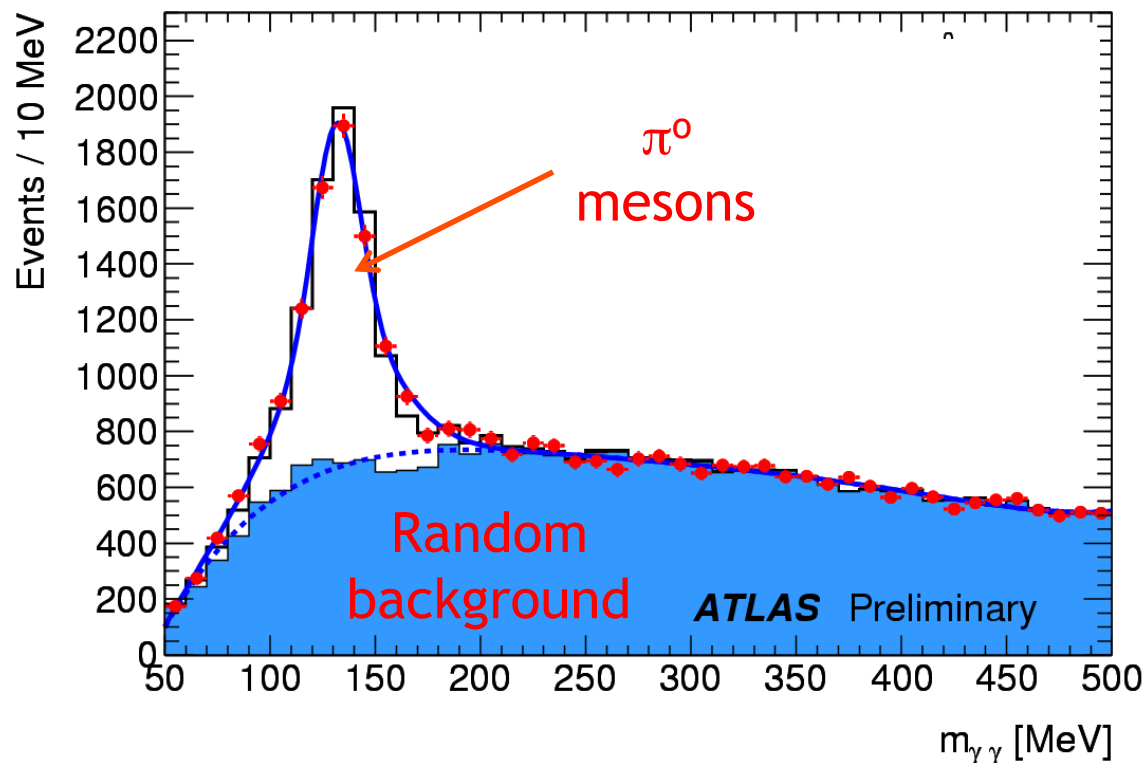


# “Seeing” Particles at the LHC

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

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

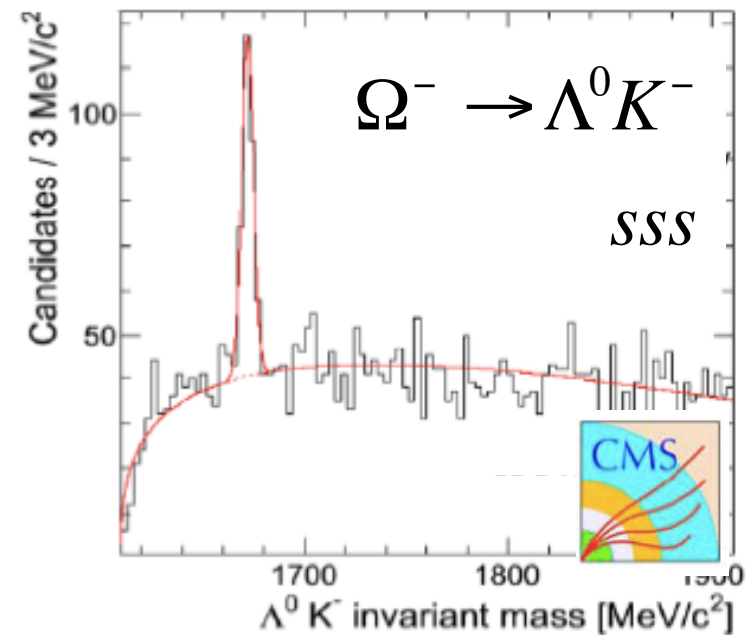
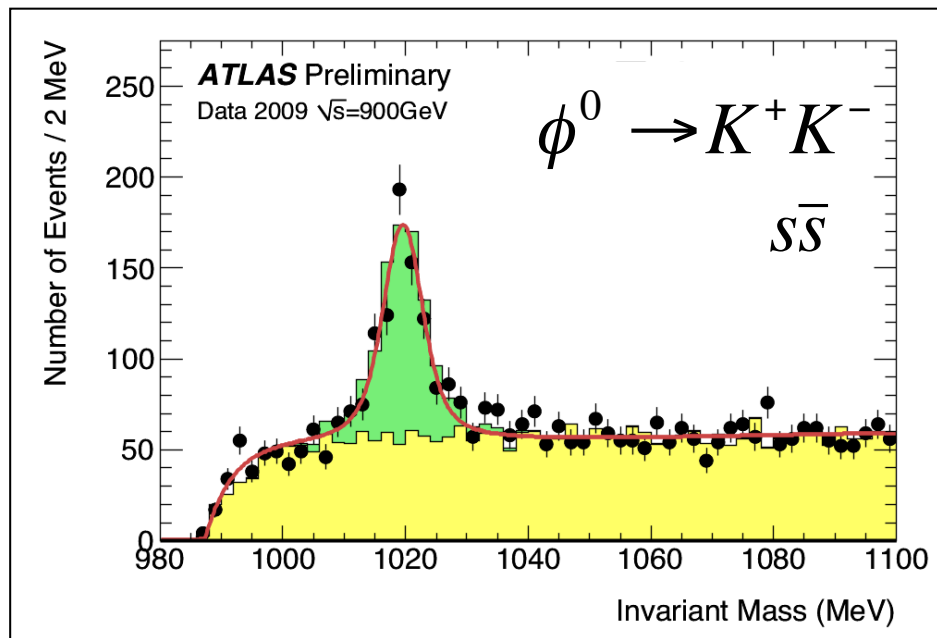
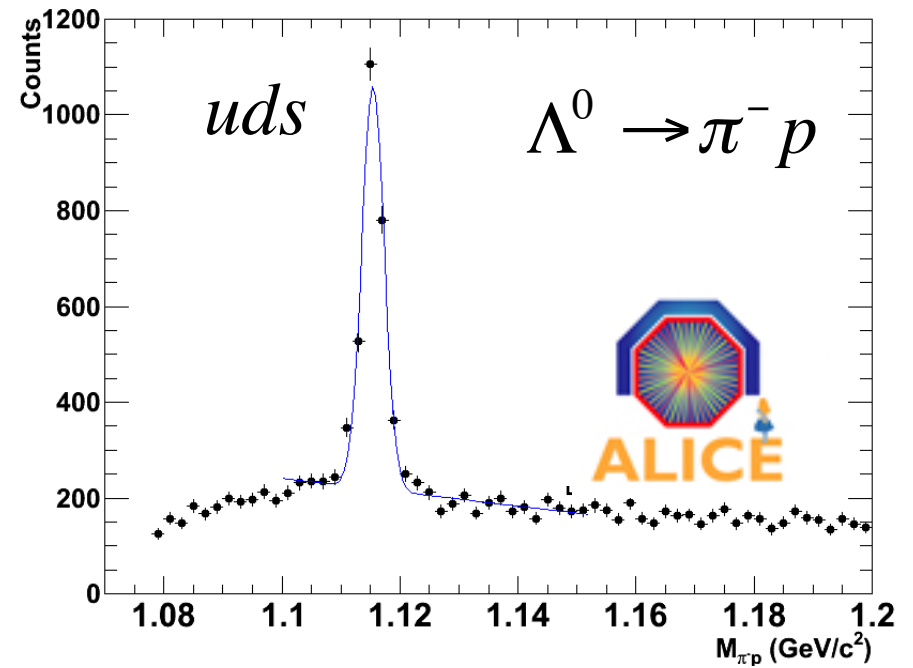
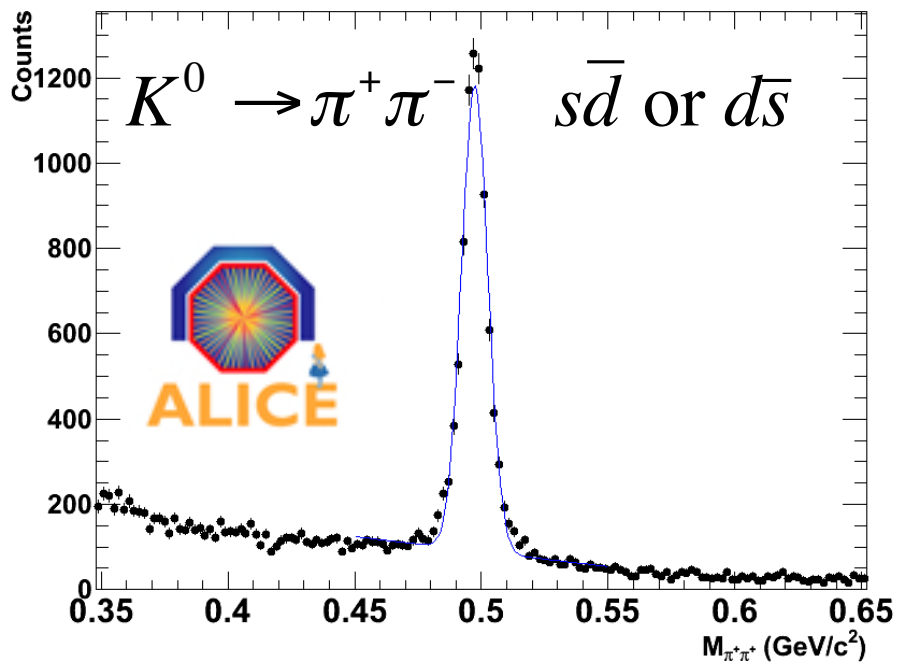
and decays fast to 2 photons .....  $\pi^0 \rightarrow \gamma\gamma$



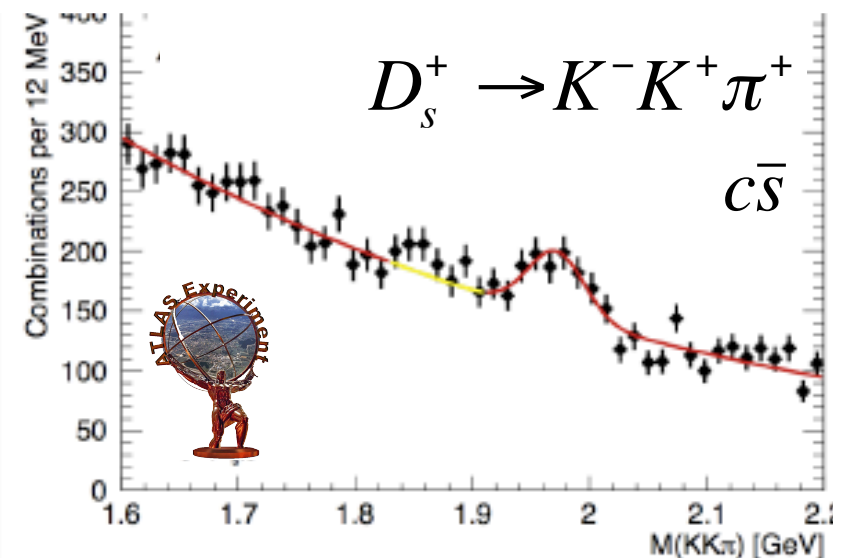
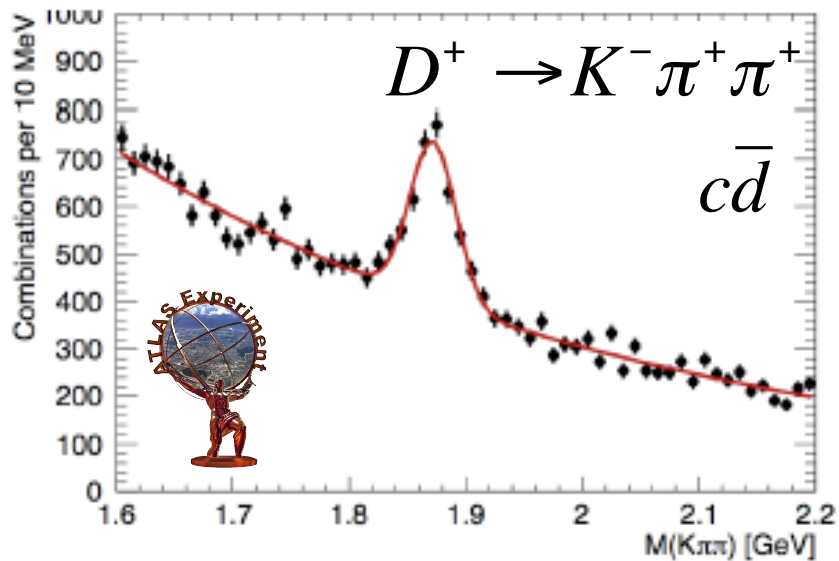
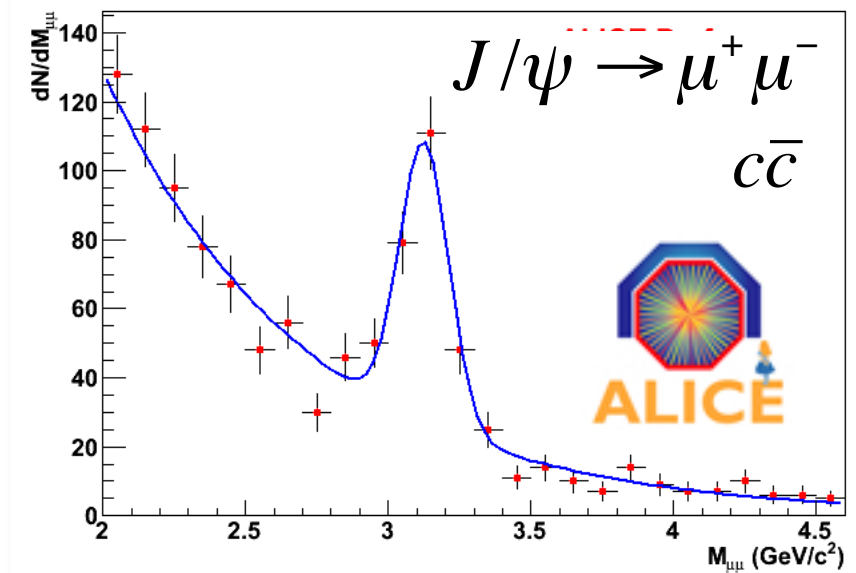
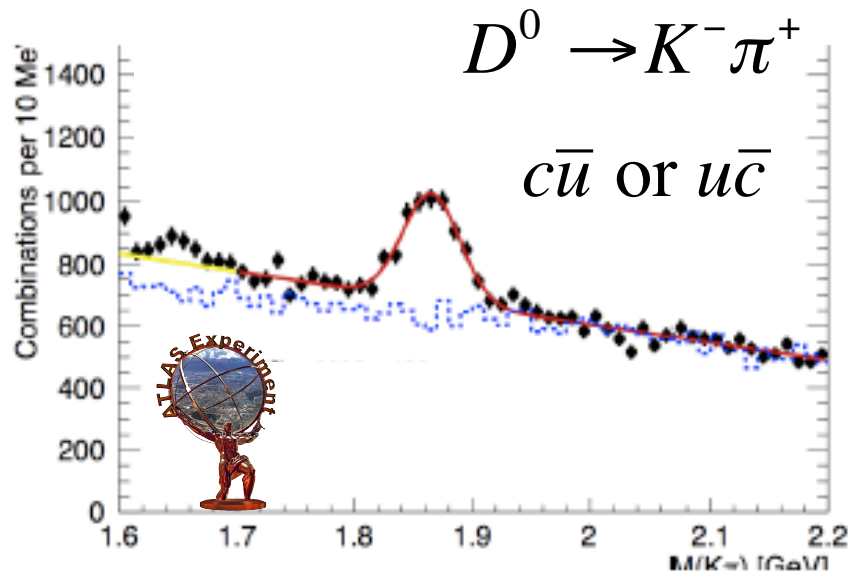
... combine all pairs of photons in every event  
... look at what particle mass they combine to give ...

One of the first LHC plots!...

# Early Strange Particle Sightings



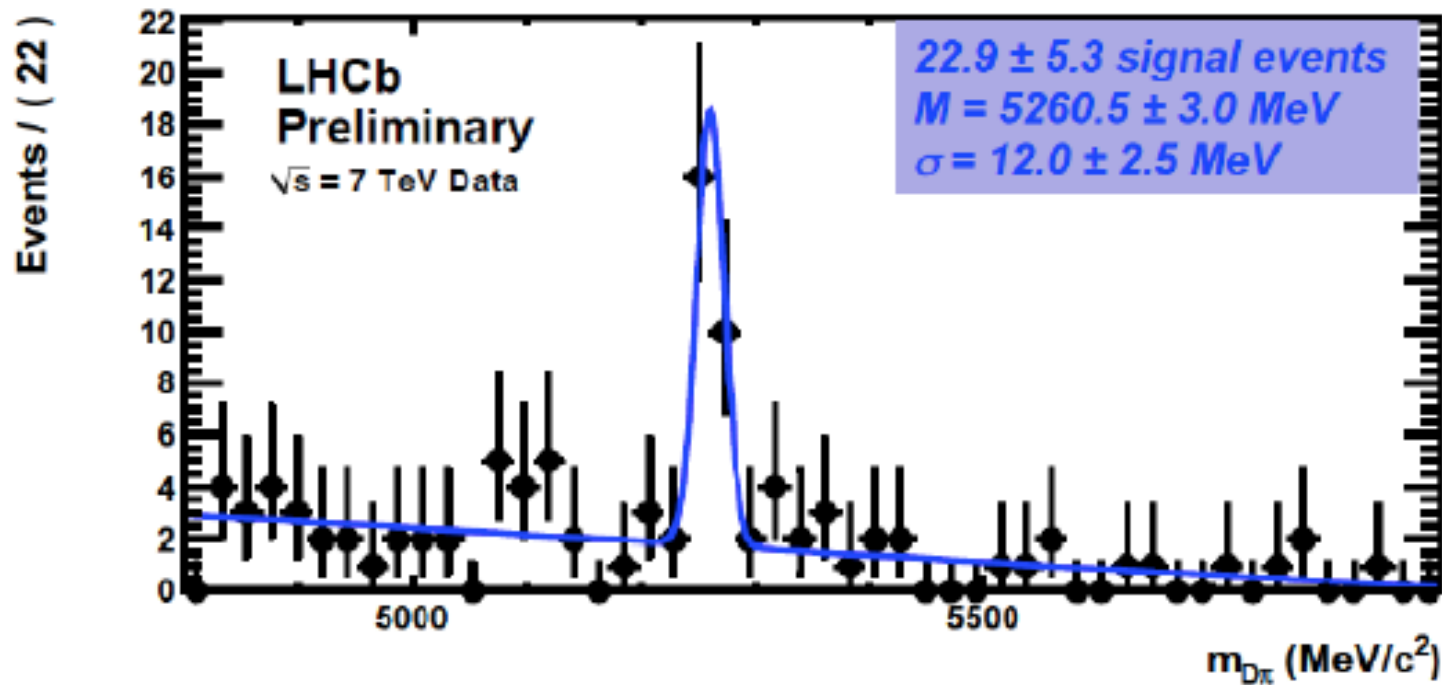
# Early Charm Particle Sightings



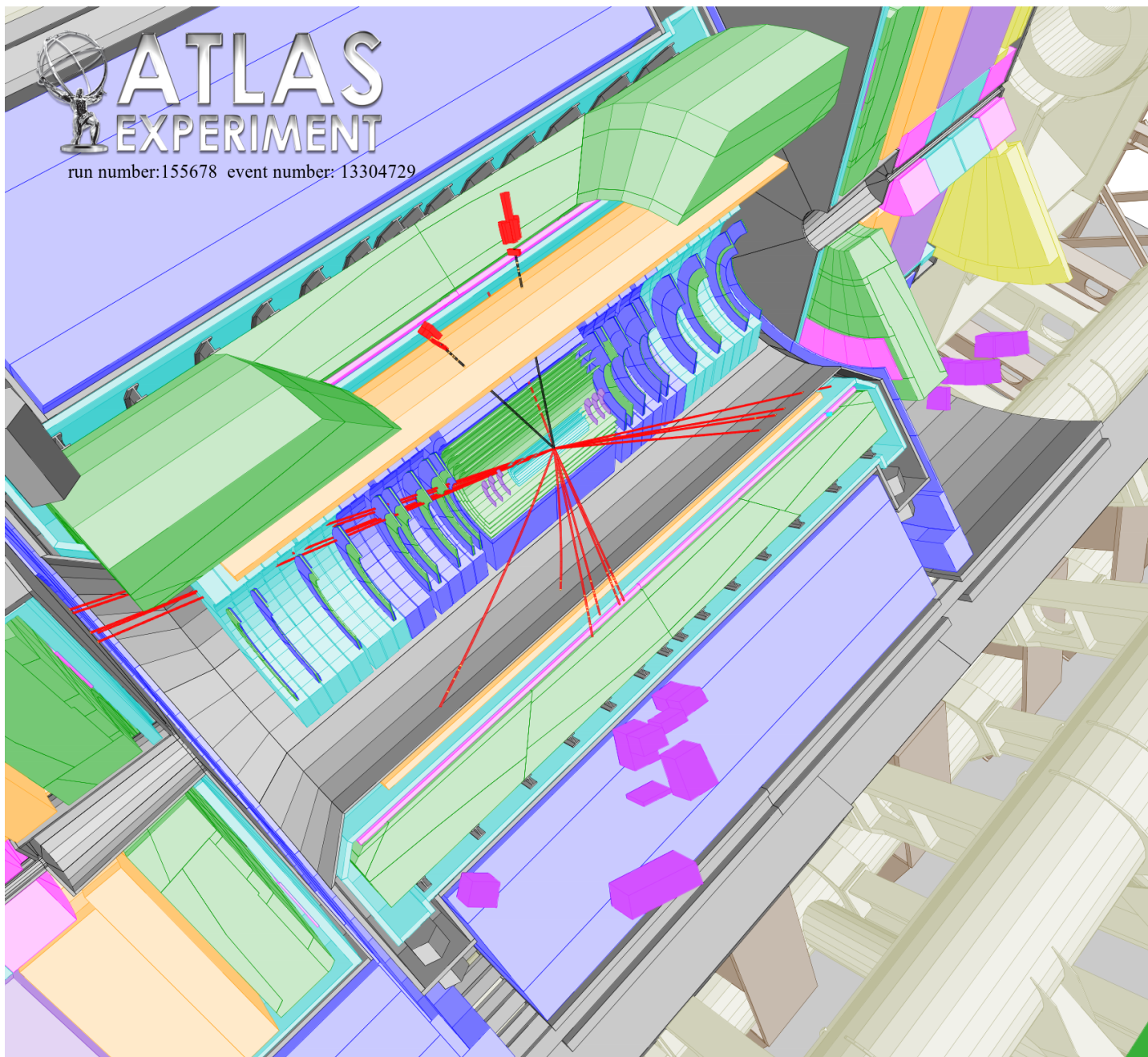
# Early Beauty Particle Sightings

$$B^0 \rightarrow D^- \pi^+ \quad \text{and} \quad B^+ \rightarrow D^0 \pi^+$$

$$b\bar{d} \quad \text{or} \quad b\bar{u}$$



# Early Top Quark Sightings



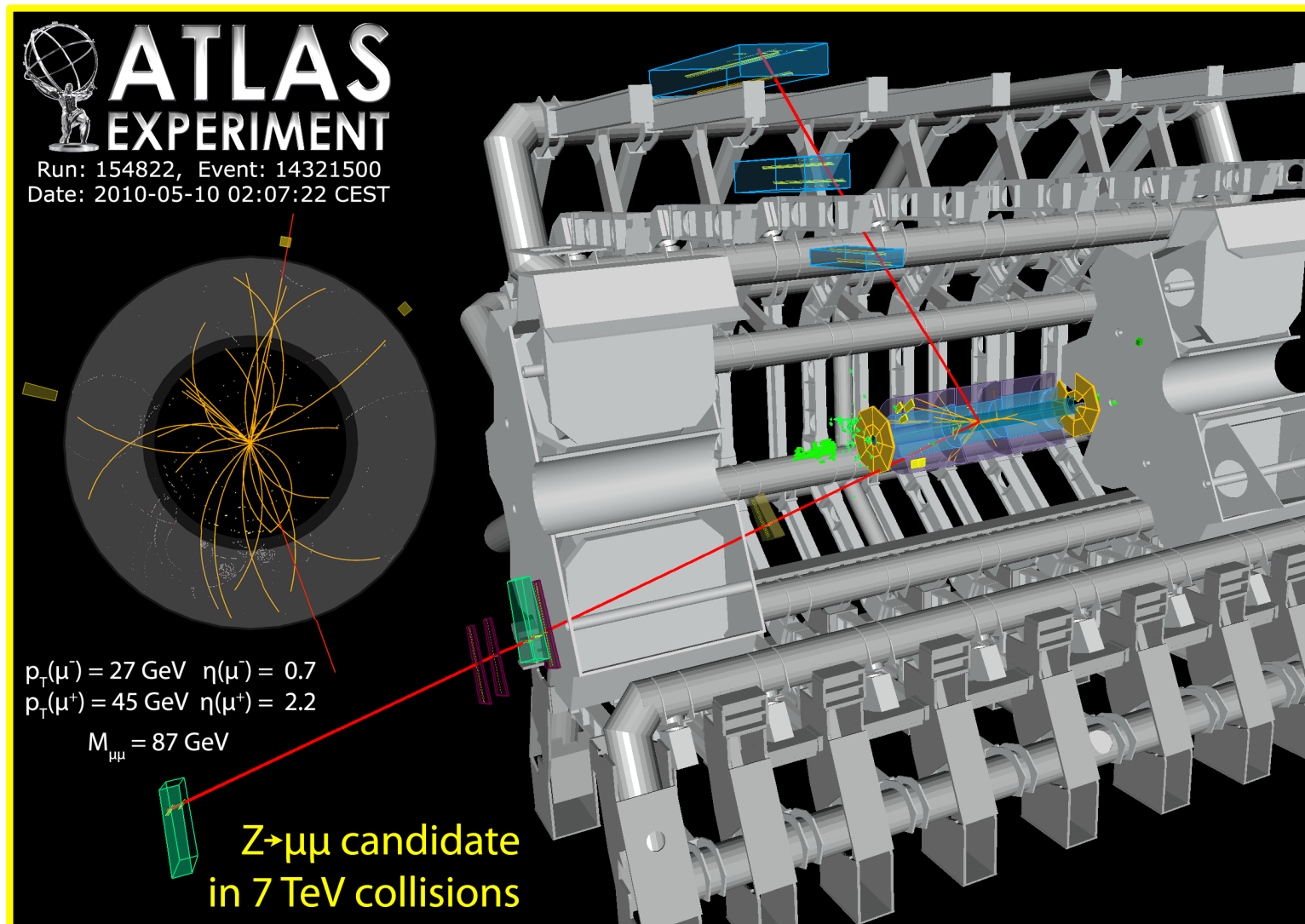
Production of a top - antitop pair.

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

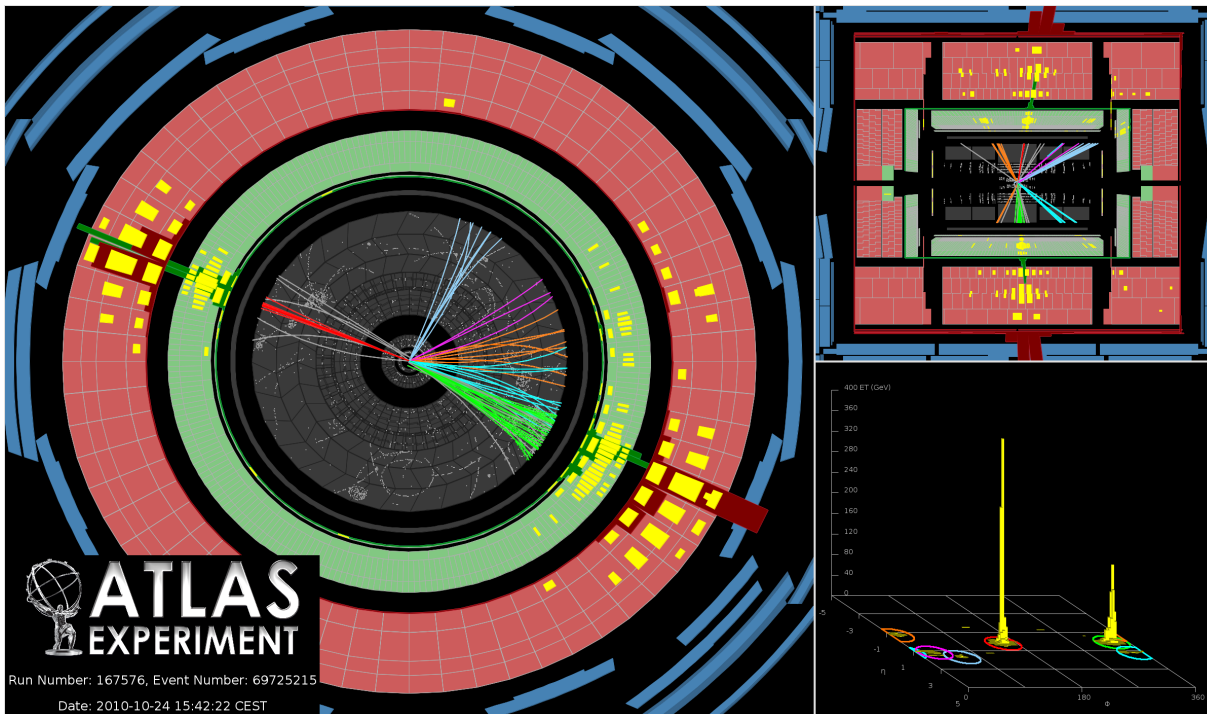
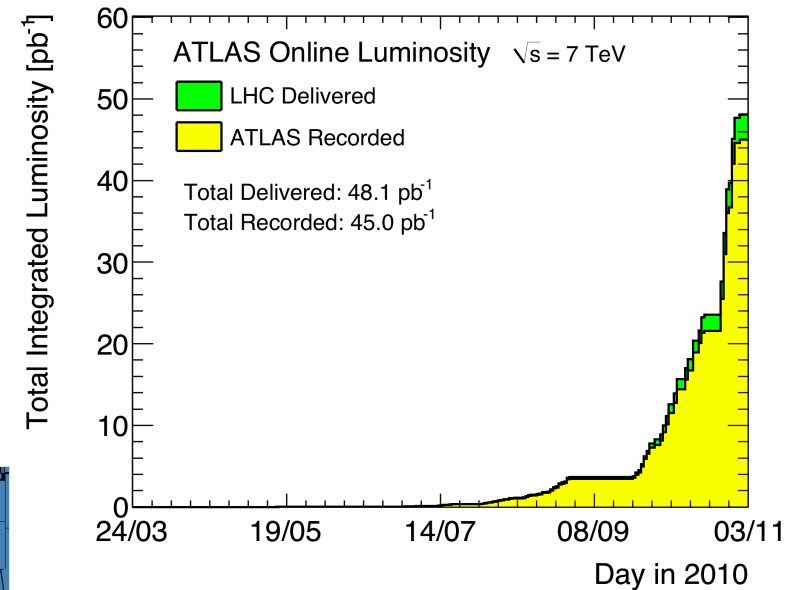
# Seeing the Weak Force Carriers



A  $Z^0$  boson decaying to  $\mu^+ \mu^-$  in the ATLAS detector

# 2010: Learning Curve

Half of 2010 collisions were delivered in the last week!



An exceptional event:  
1st jet:  $p_T = 1.3$  TeV,  
2nd jet:  $p_T = 1.2$  TeV  
2 jet mass = 2.6 TeV

From 2010 data: Quarks must be smaller than  $5 \times 10^{-20}$  m!

# 2011 Data

In 2011 we have already collected 25 times more data than 2010 ...  
... expect another factor of 4 this year

... the first serious searches for the unexpected will be released in 2 weeks

... Watch the news!



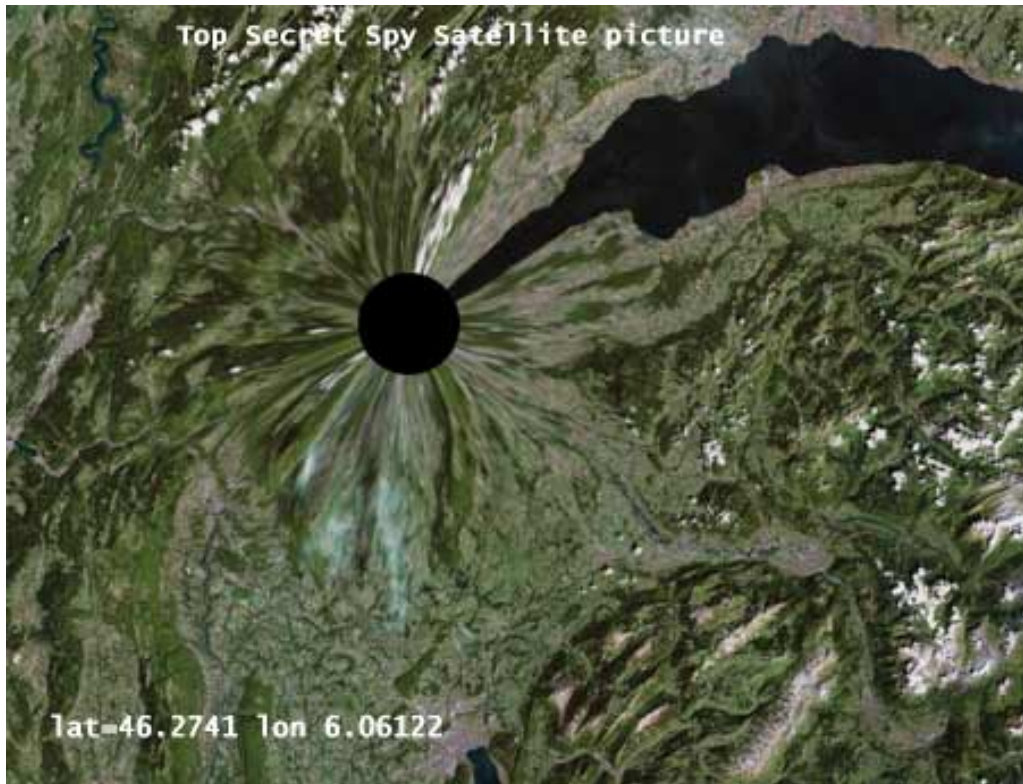
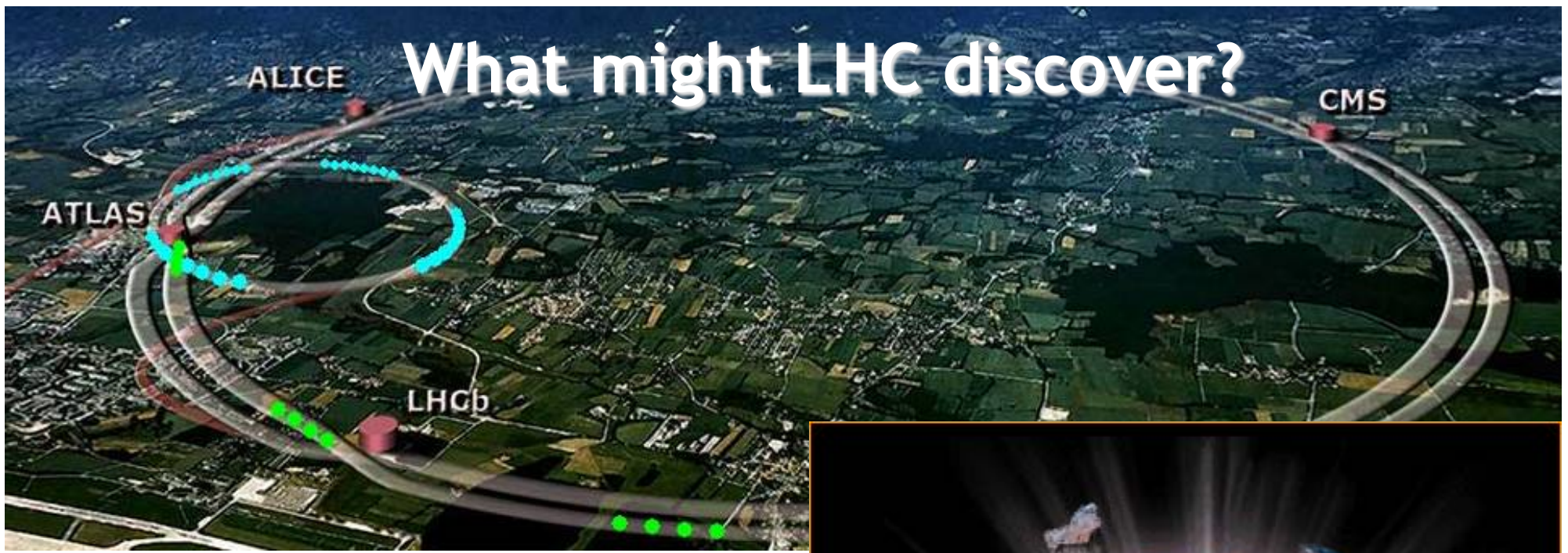
International Europhysics Conference on High Energy Physics  
Grenoble, Rhône-Alpes France July 21-27 2011

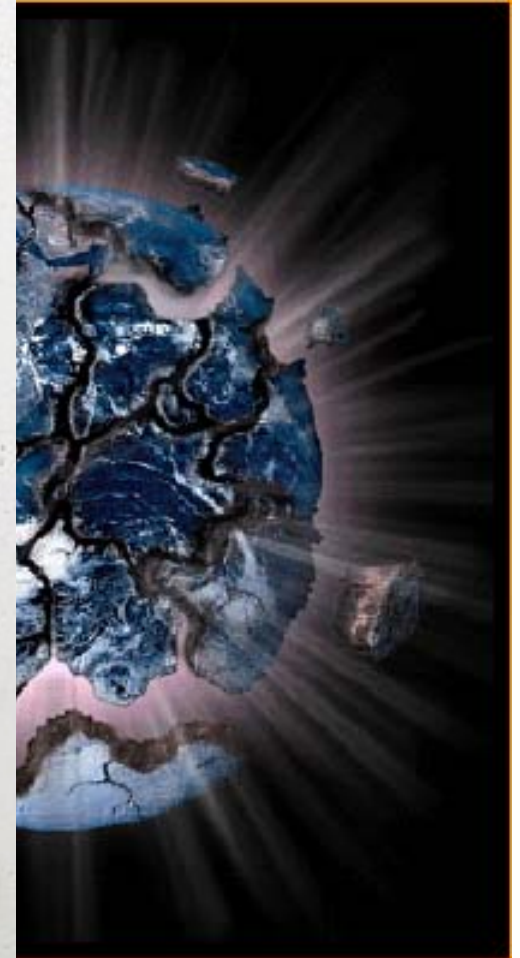
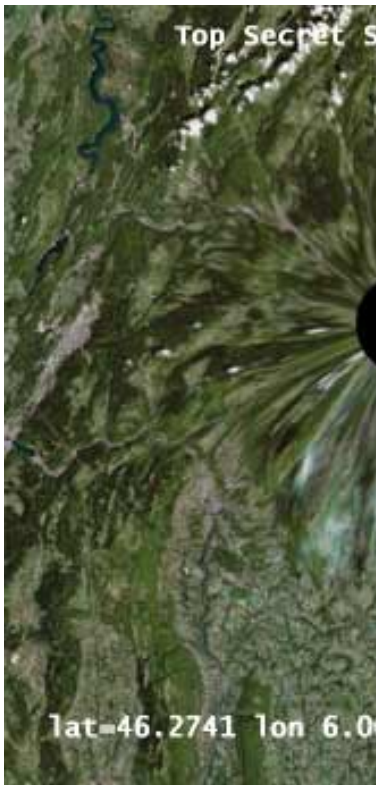
European Physical Society

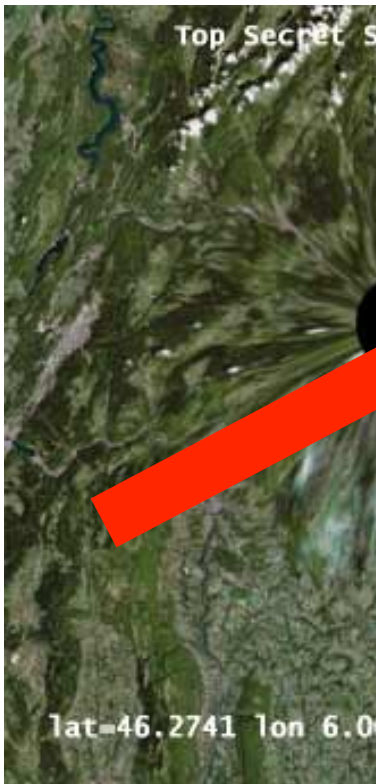
HEP 2011



# What might LHC discover?

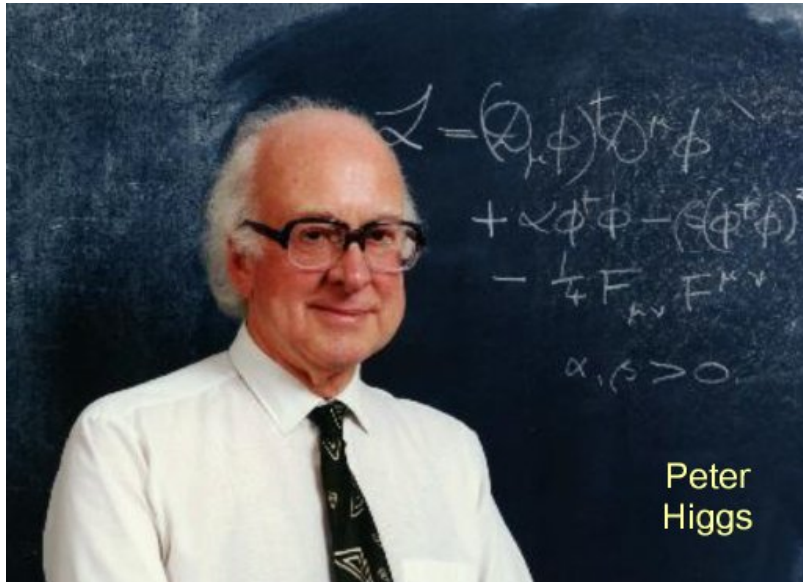






# What might the LHC Discover?...

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

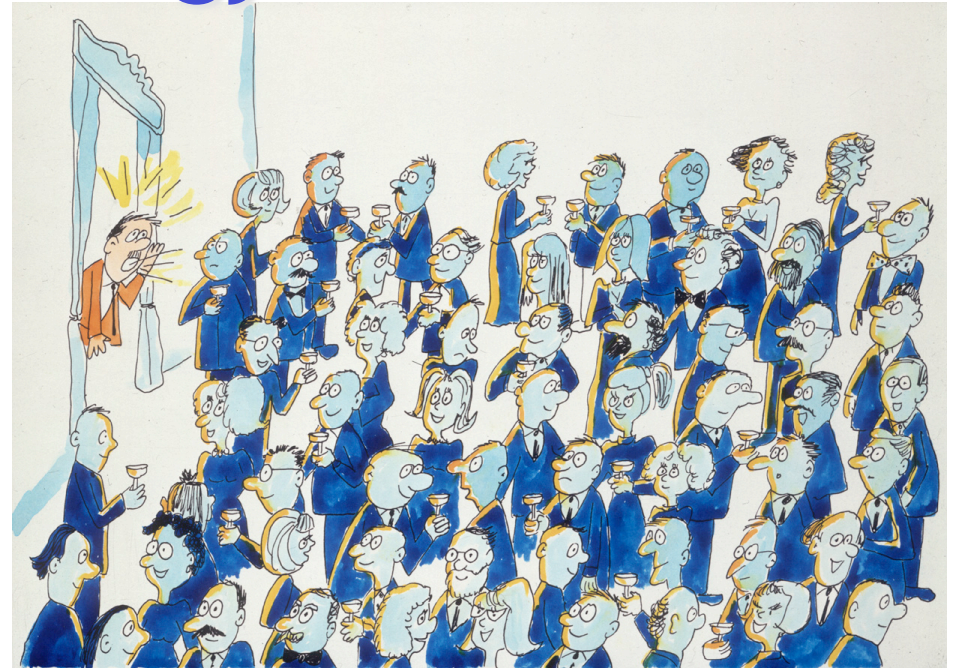


In the mid 1960s, British physicist Peter Higgs came up with a theory

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?...

... trouble is we haven't seen the Higgs boson yet ☹



## 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.

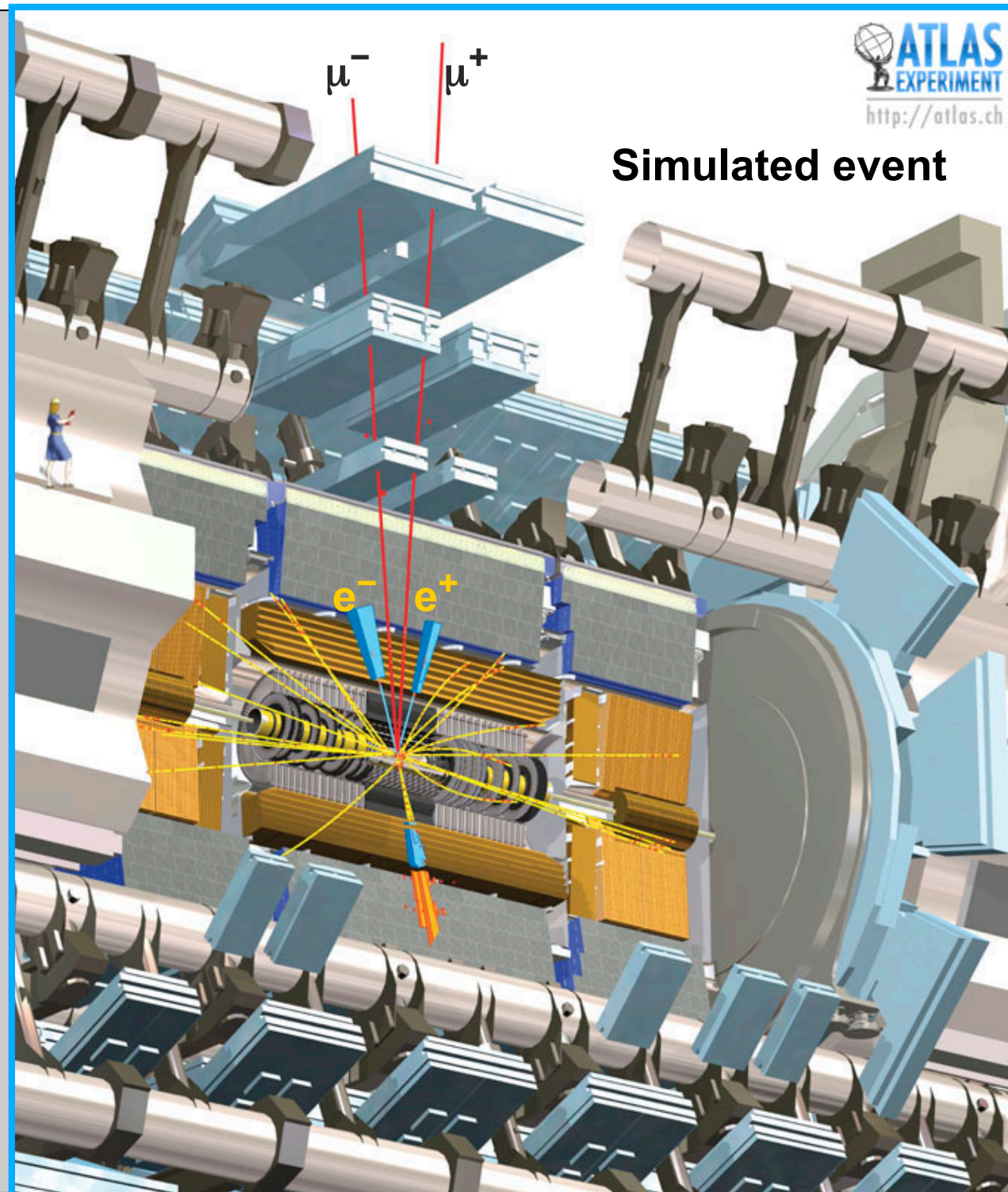
$$H \rightarrow Z + Z$$

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

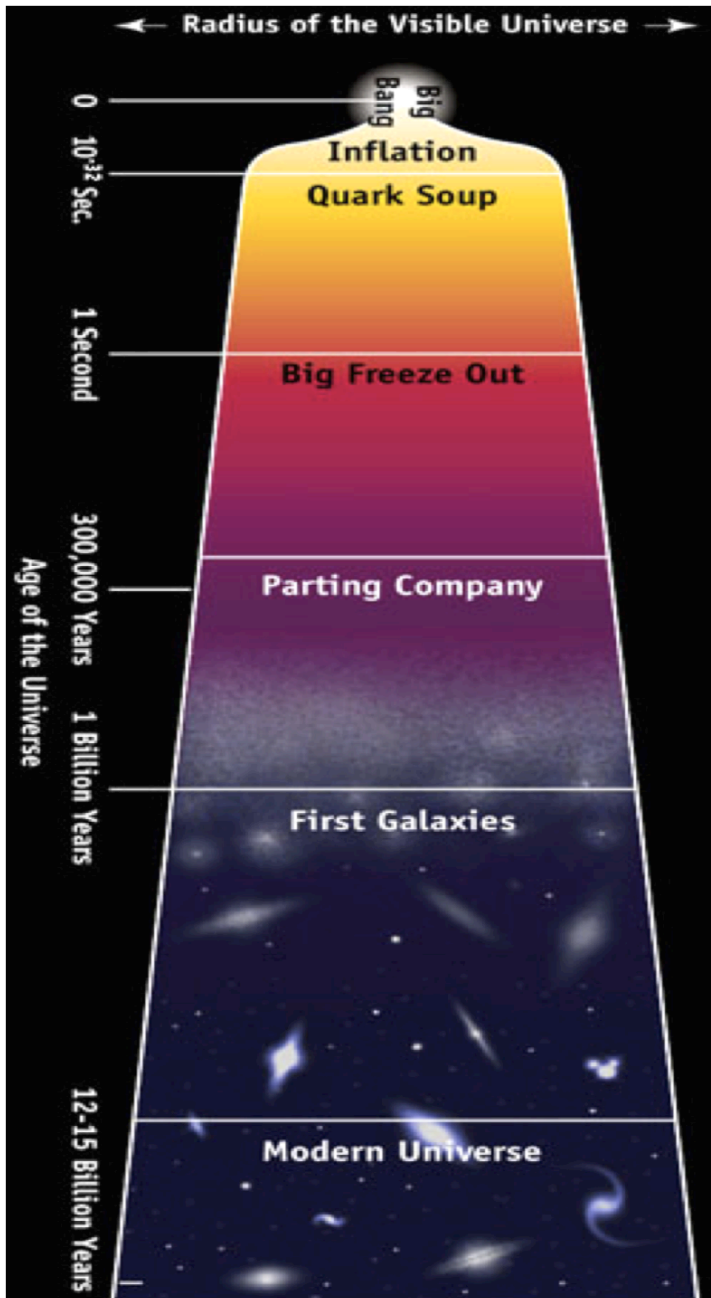
$$Z \rightarrow \mu^- + \mu^+$$

1 billion events per second

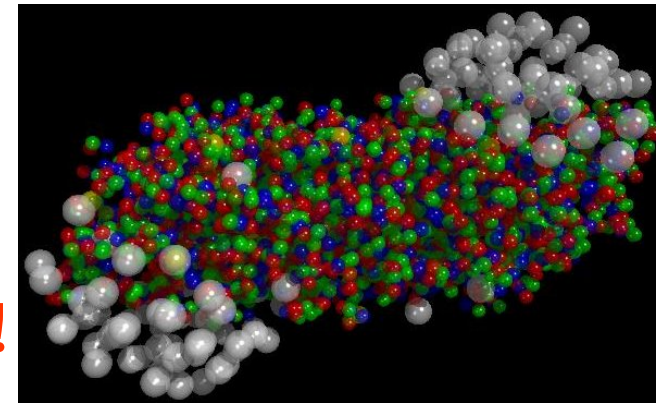
1 Higgs produced every 10 seconds!



# 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 ‘Quark-Gluon Plasma’)

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

... when the temperature of the universe was  $\sim 10^{13}$  °C!

# LHCb & the Matter/Antimatter Puzzle.

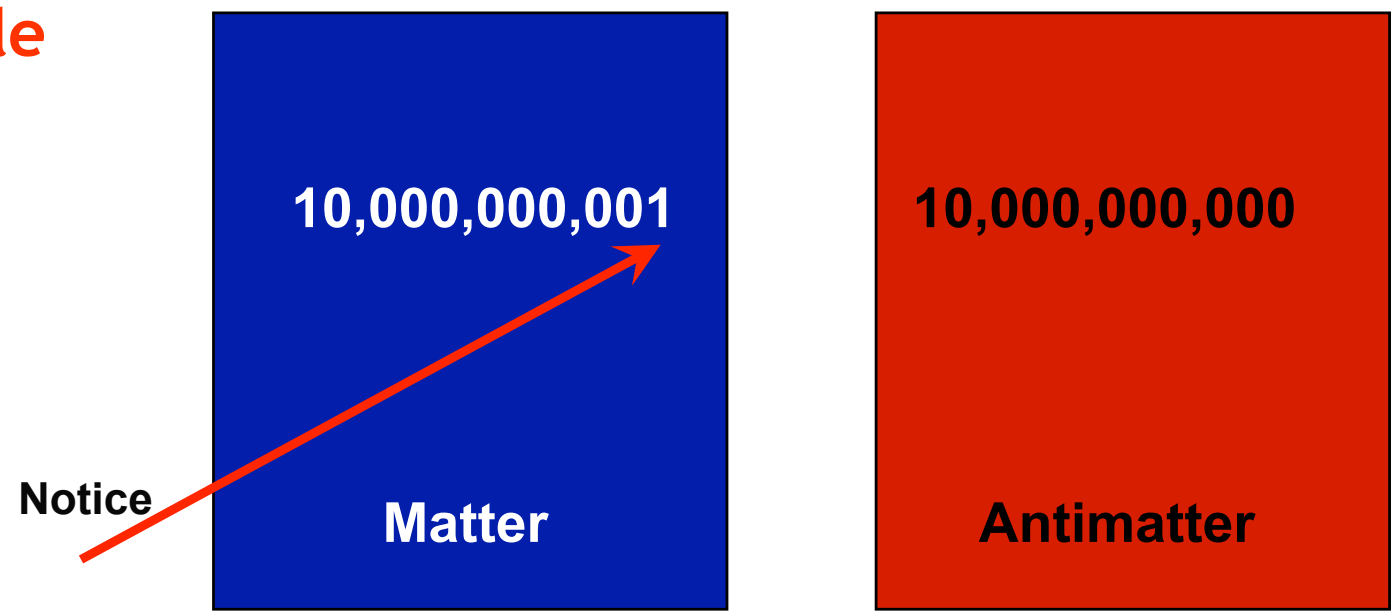
... if the big bang gave us equal amounts of matter and antimatter, where did all the antimatter go?...



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

... so a possible answer ...

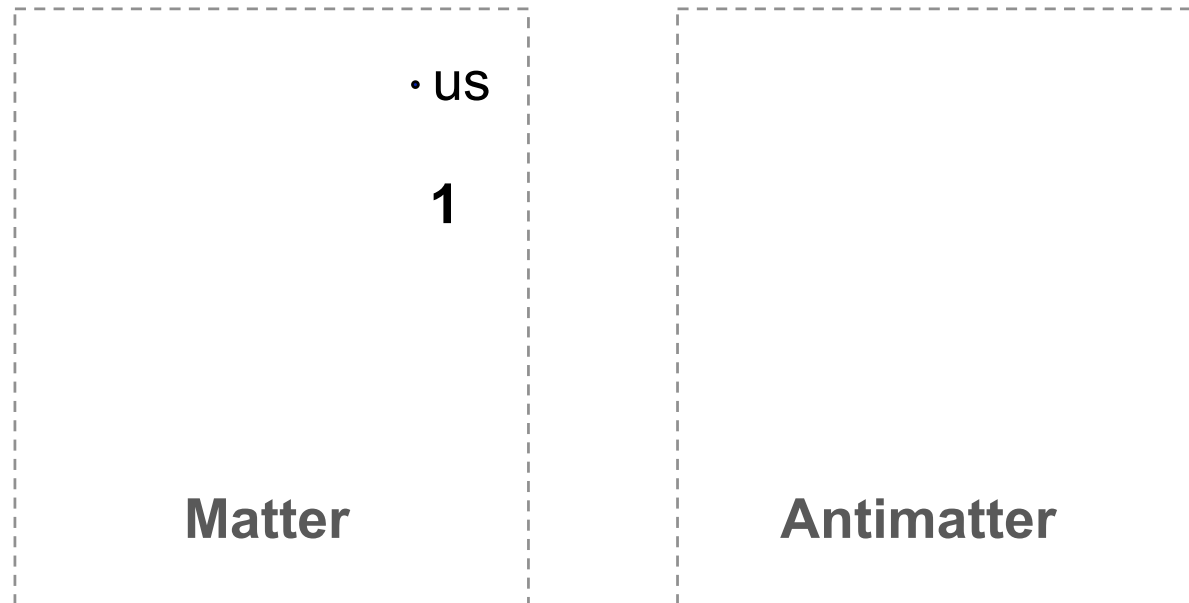
sometime just after the big bang ...



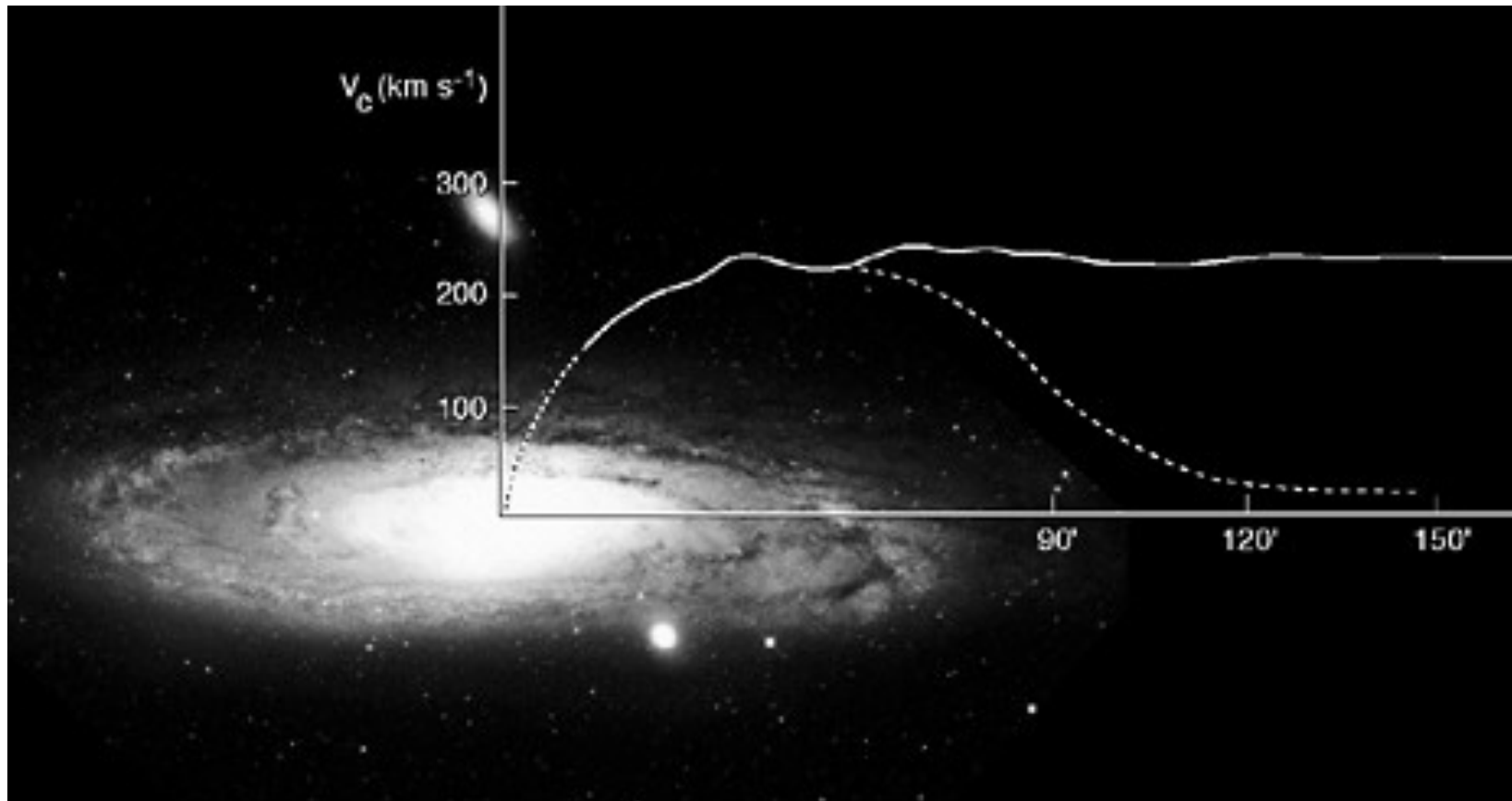
# Where is all the Antimatter?

... a great annihilation then took place ...

... leaving only a “tiny” part of the matter ... us!



# A connection to the Universe

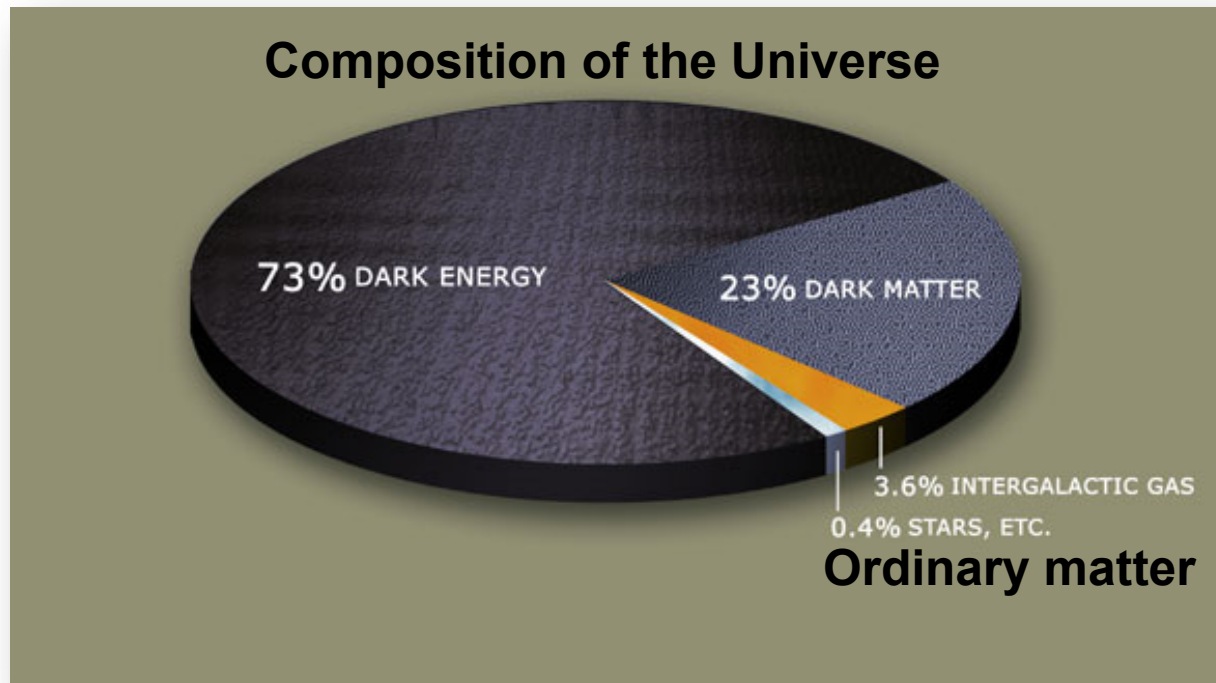


Looking at the relative rotation and gravitational attraction deep in the universe, either ...

- 1) Einstein'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)



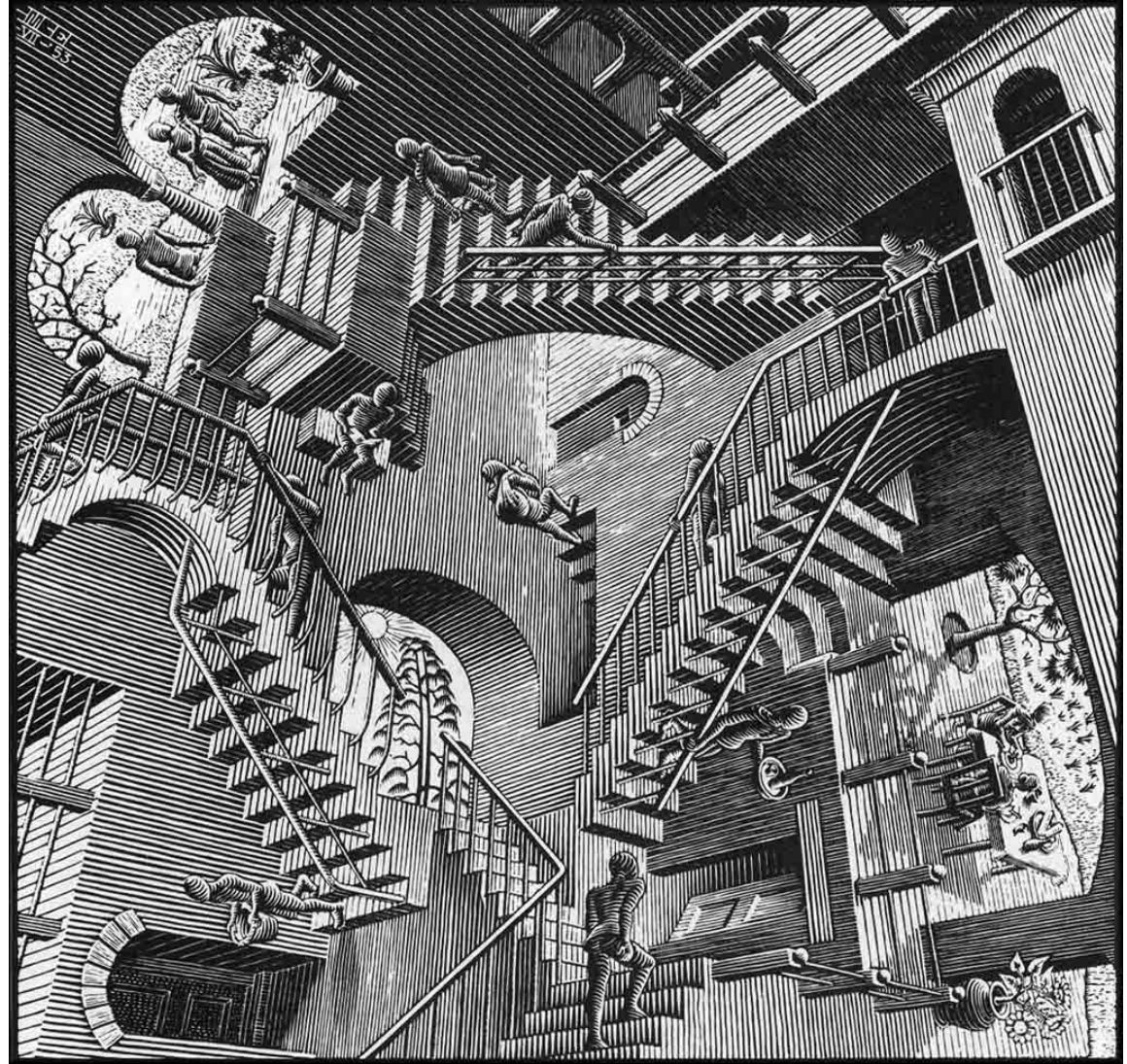
The dark side of  
the universe...



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

# Are there New Unknown Dimensions?

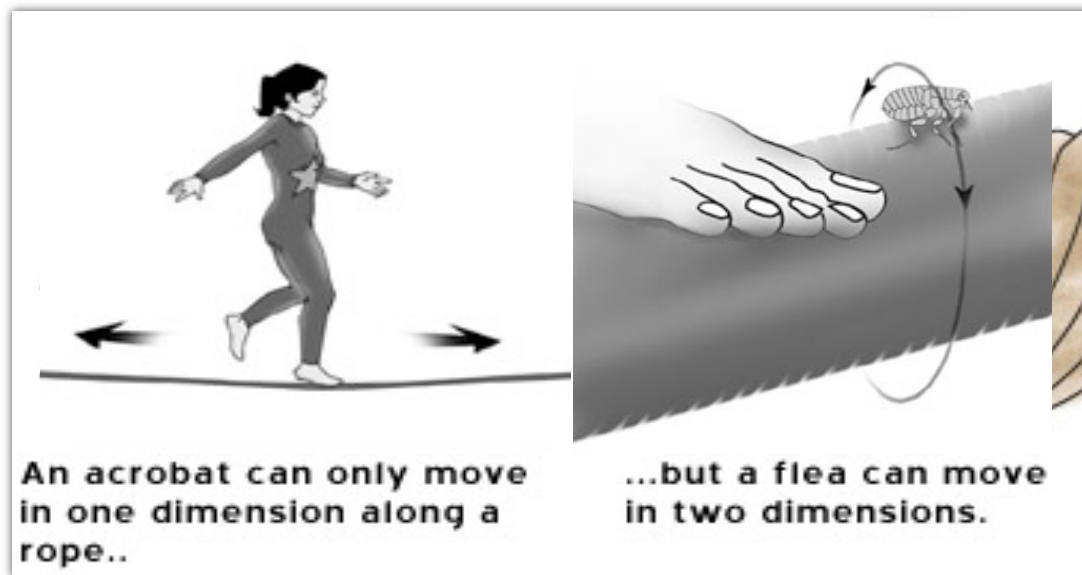
- Could explain why gravity is so extremely weak?...
- Maybe it is really stronger, but operates in more dimensions and we feel only its relics?
- ... could give rise to the production of mini black holes at the LHC
- it's OK ...they're quite safe 😊



# 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.



Maybe there could be imperceptible 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

→ 10% of design collision rate

• 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!**