

An Introduction to Particle Physics & Accelerators

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UNIVERSITY OF
BIRMINGHAM

Particle Physics Masterclass
6 April 2011

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

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

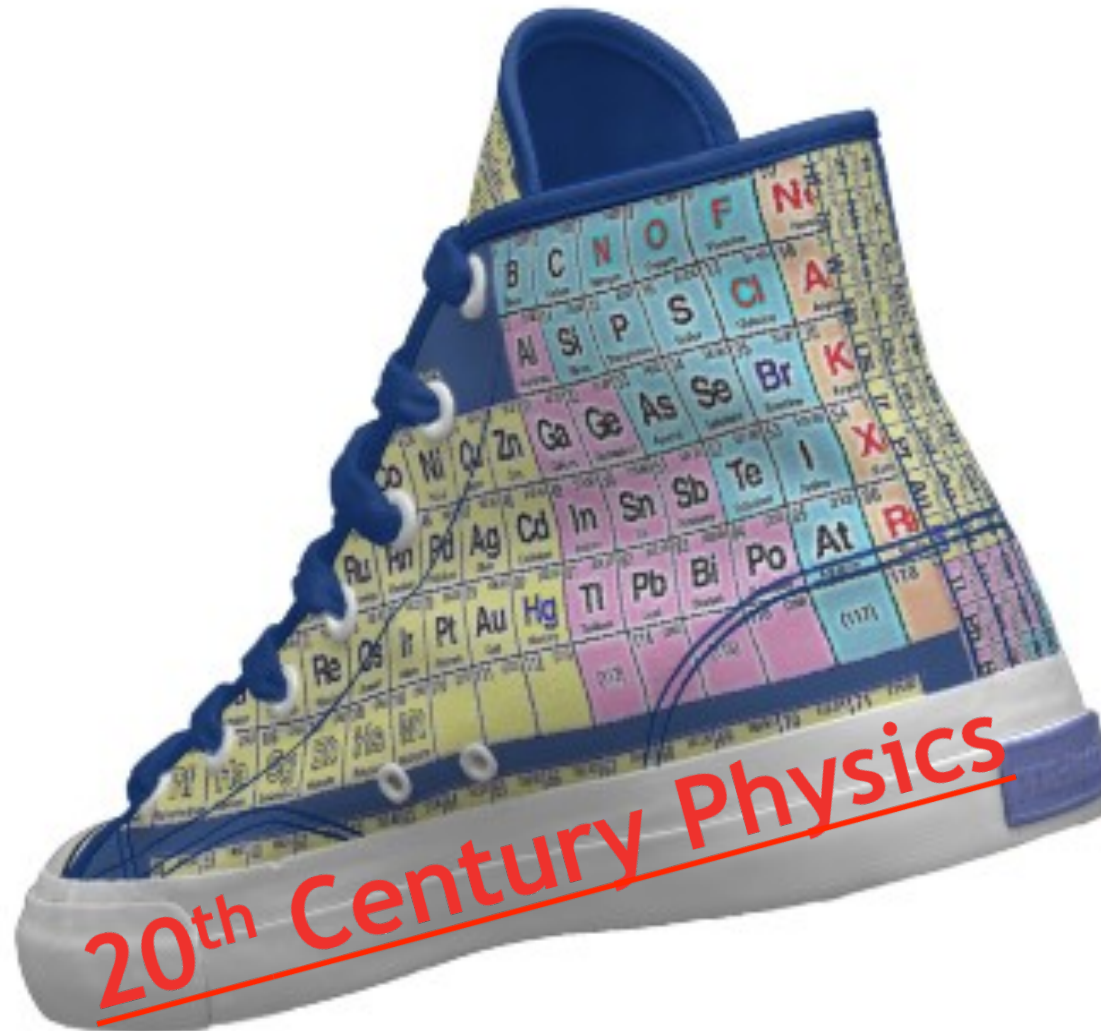
58 Ce Cerium 140.116	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04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

"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

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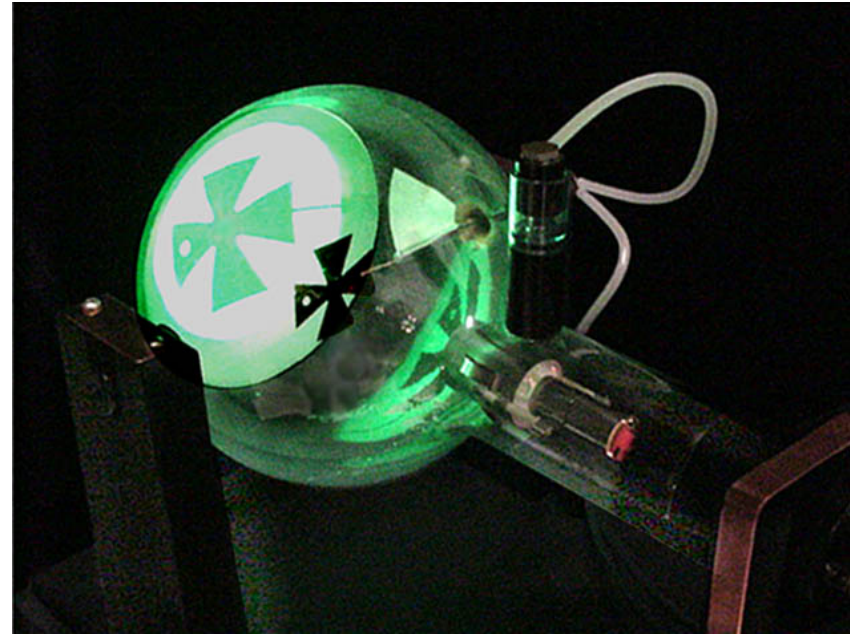
"There is
All that

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nt."
900

Cathode Ray Tubes

High Voltage passed
across low pressure gas

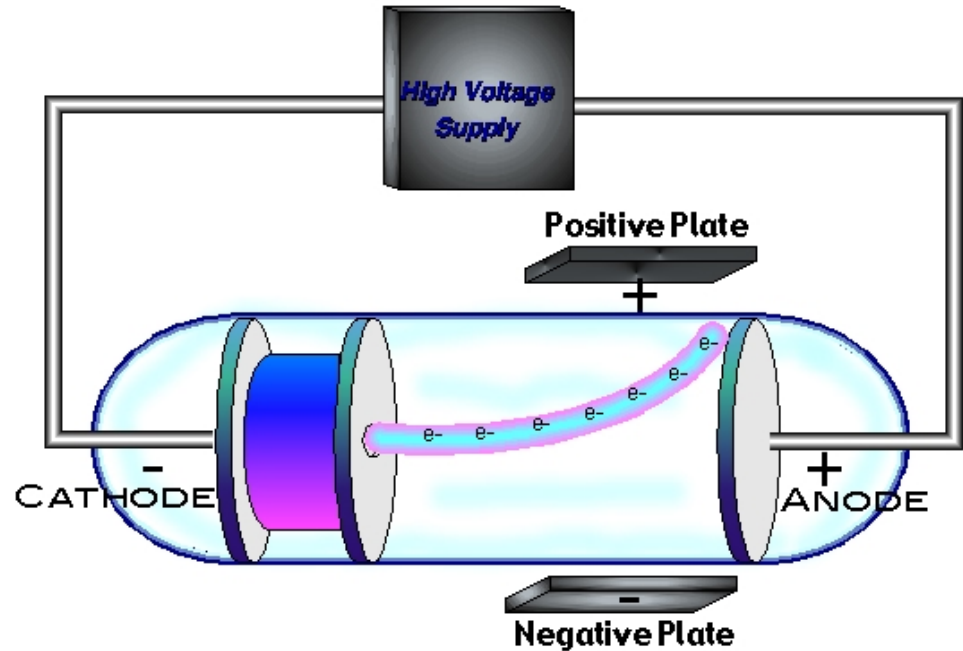
Mysterious charged particles
emitted from cathode



Cathode Ray Tubes

High Voltage passed across low pressure gas

Mysterious charged particles emitted from cathode



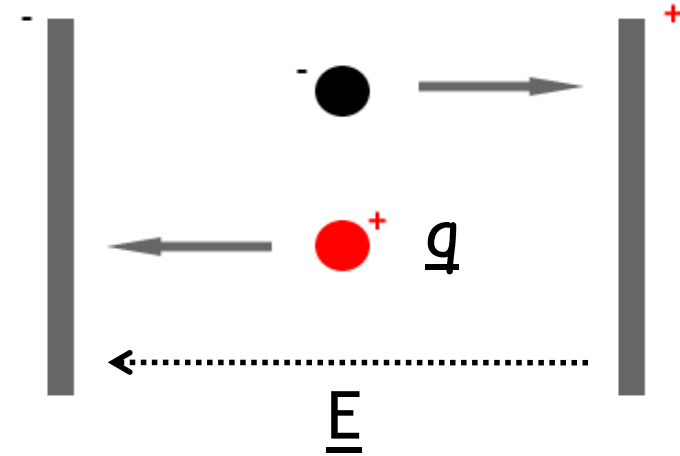
1897: JJ Thompson measured cathode ray mass from bending in electric field

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

Electric & Magnetic Forces on Charges

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

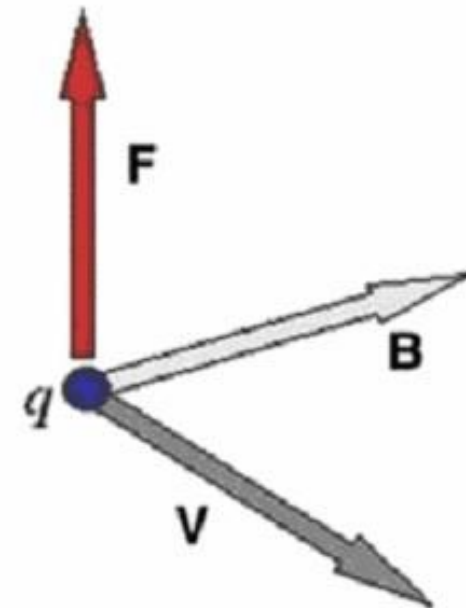
$$F = ma = qE$$



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

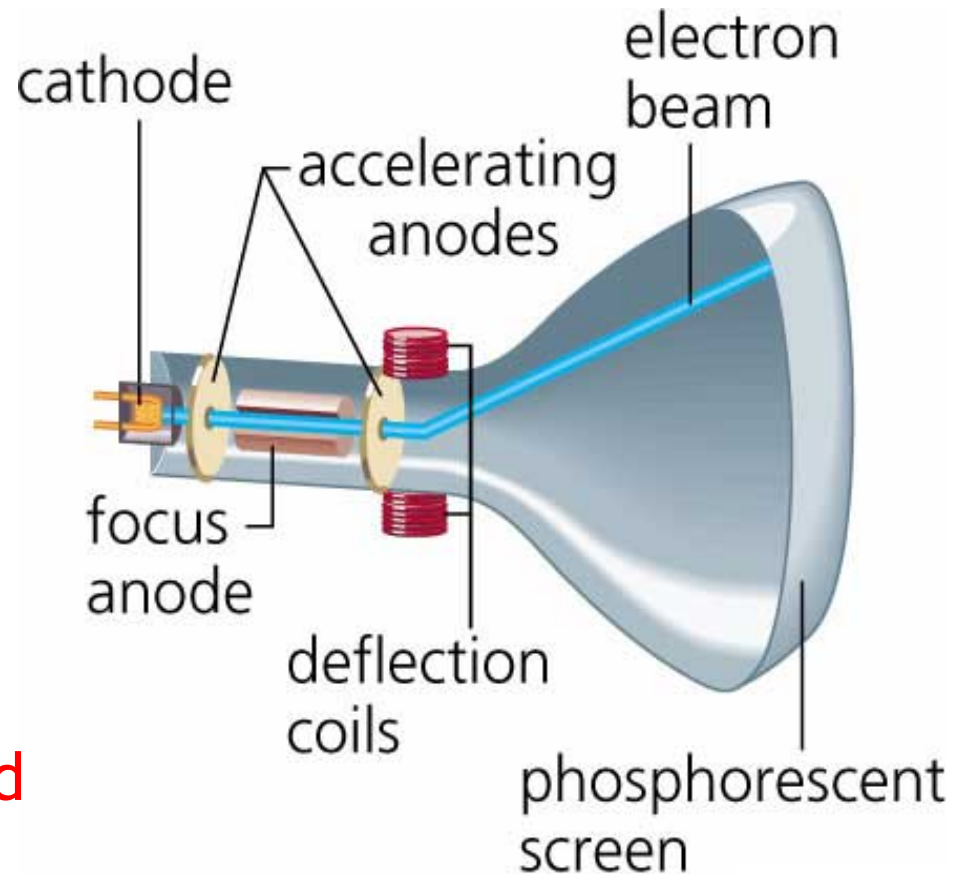
Particle physics accelerators work on same principles!

A USEFUL UNIT

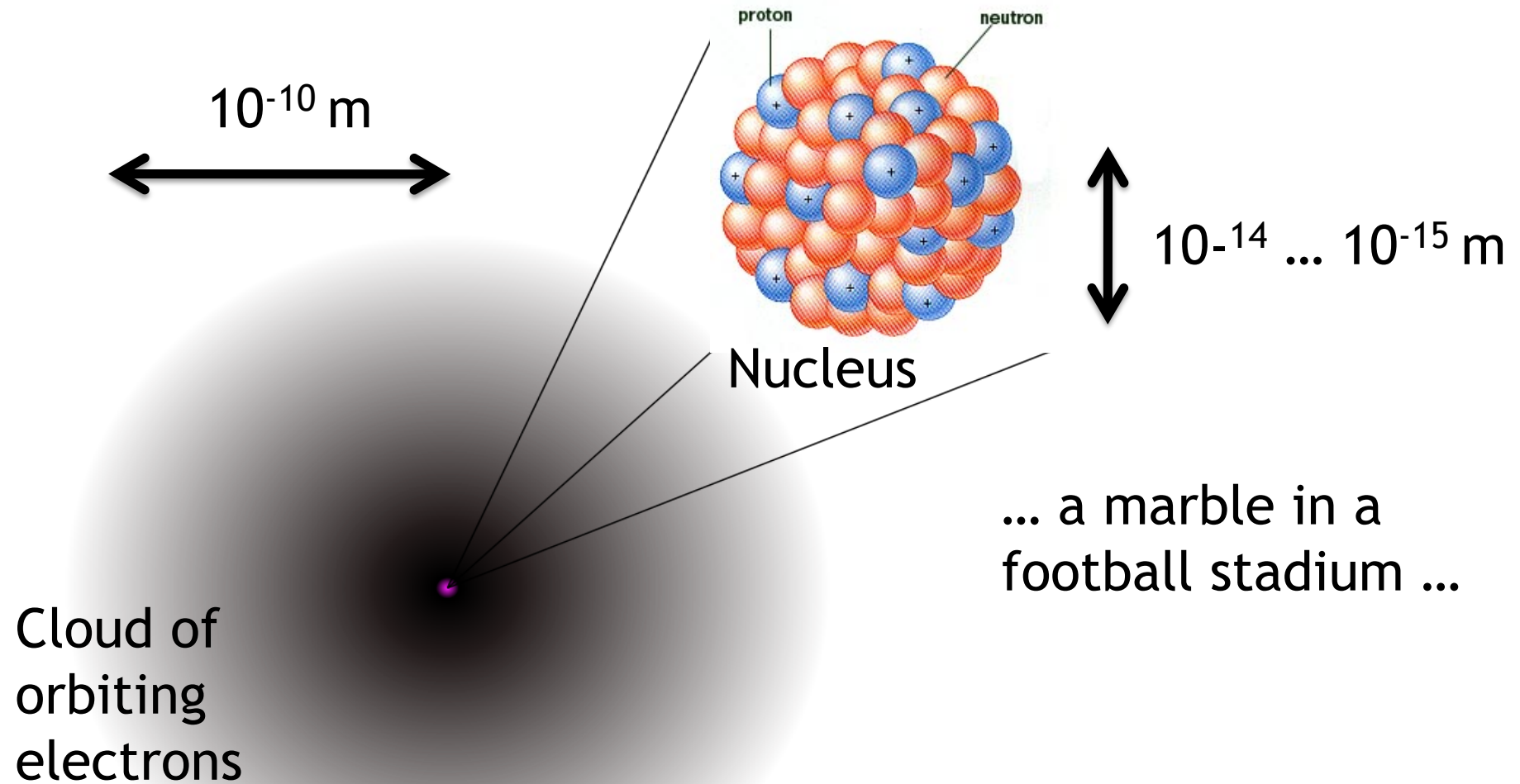
A particle of charge q accelerated through a potential difference V acquires a kinetic energy $KE=qV$.

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

- A cathode ray tube TV accelerates electrons to ~ 20 keV



A Modern Picture of the Atom



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

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

SLAC 1969: A very long “cathode ray tube”

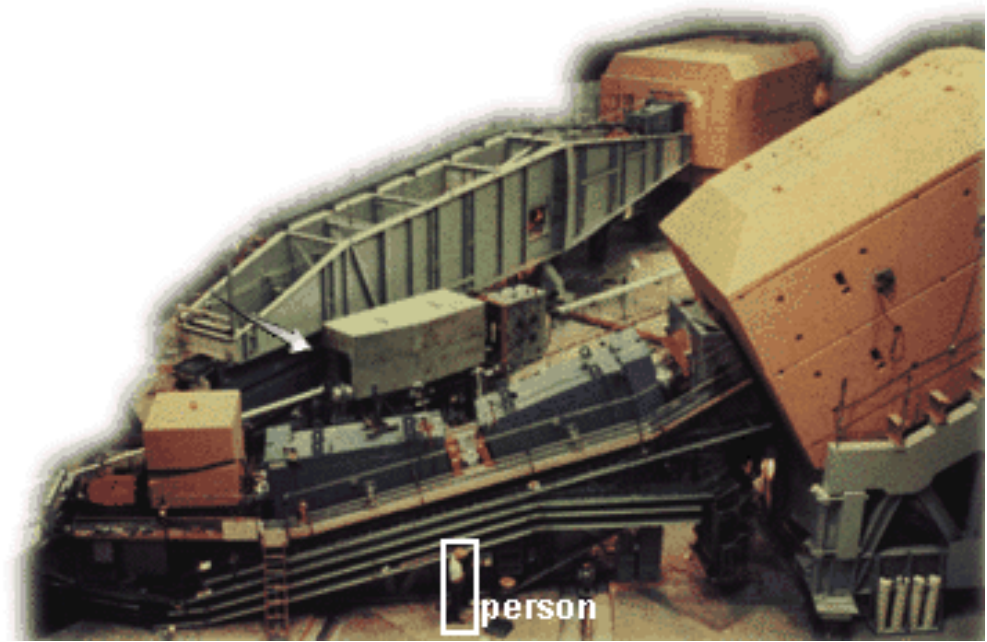


Accelerating electrons to
 $20 \times 10^9 \text{ eV} = 20 \text{ GeV}$

... Collisions with a fixed
proton target gave
surprising results



SLAC 1969: A very long “cathode ray tube”



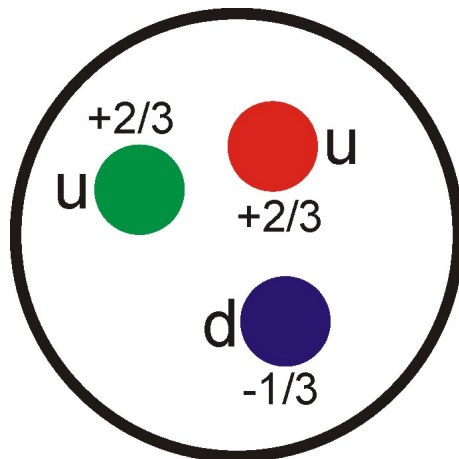
What the SLAC experiment saw

Electrons were hitting “point” charges inside the proton

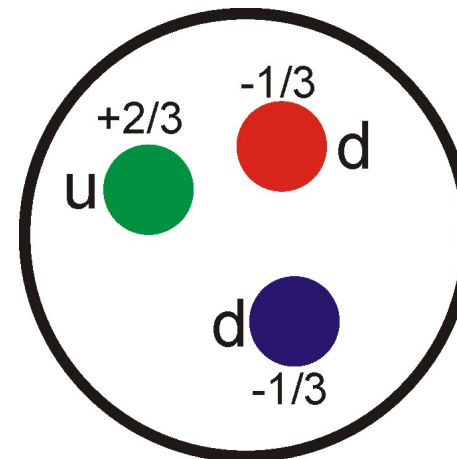
“Three quarks for Muster Mark!”

[James Joyce, *Finnegan’s Wake*]

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



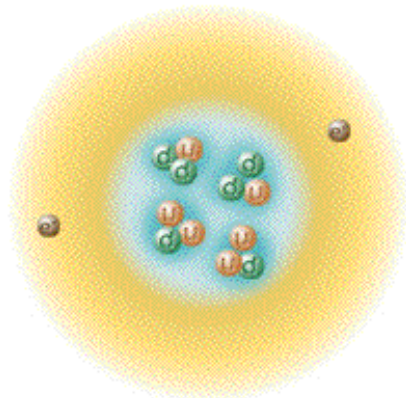
Proton



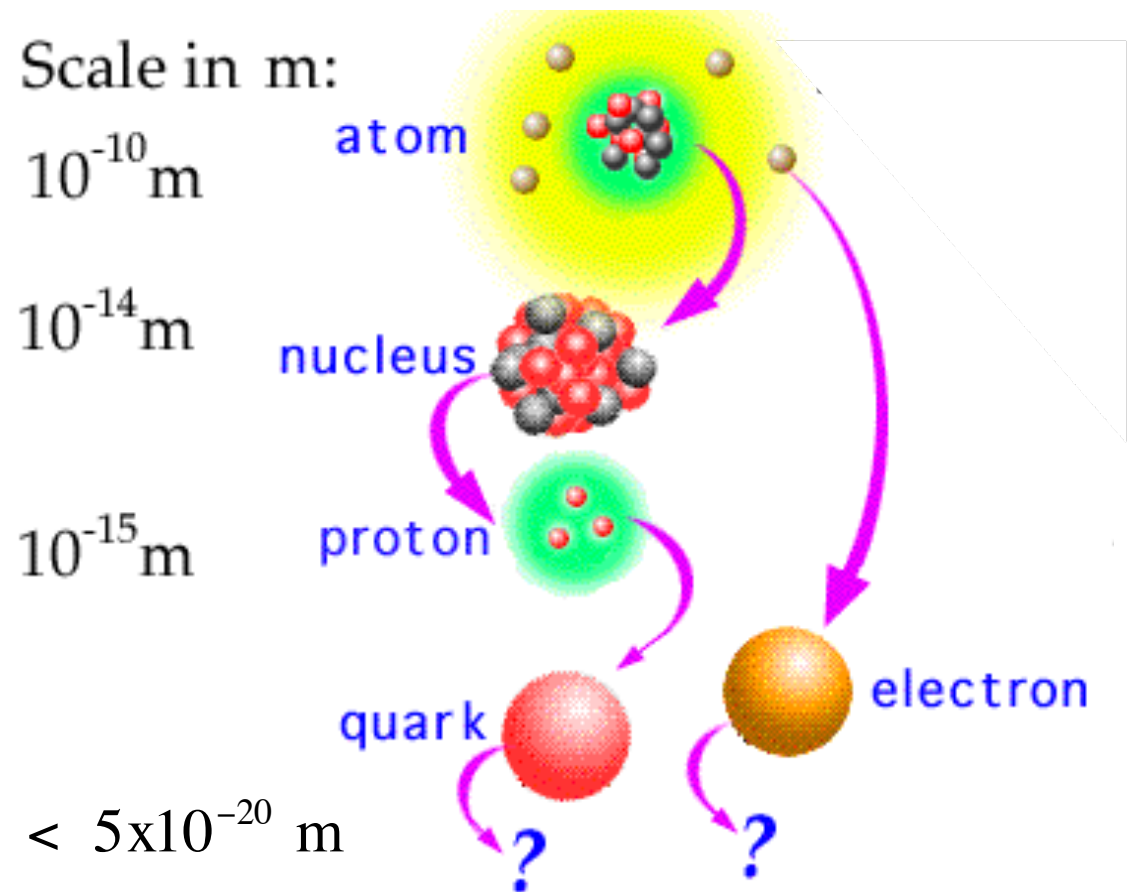
Neutron

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.



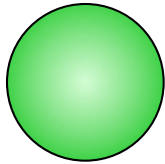
- Nuclei consist of protons and neutrons.
- The protons and neutrons are made of **quarks**.



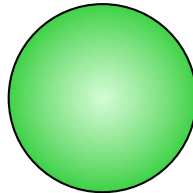
... A Nice Happy Family of Particles



Up quark (u)



Down quark (d)



Electron (e⁻)



Electron neutrino (ν_e)



Mass ~ 0.003

~ 0.006

= 0.0005

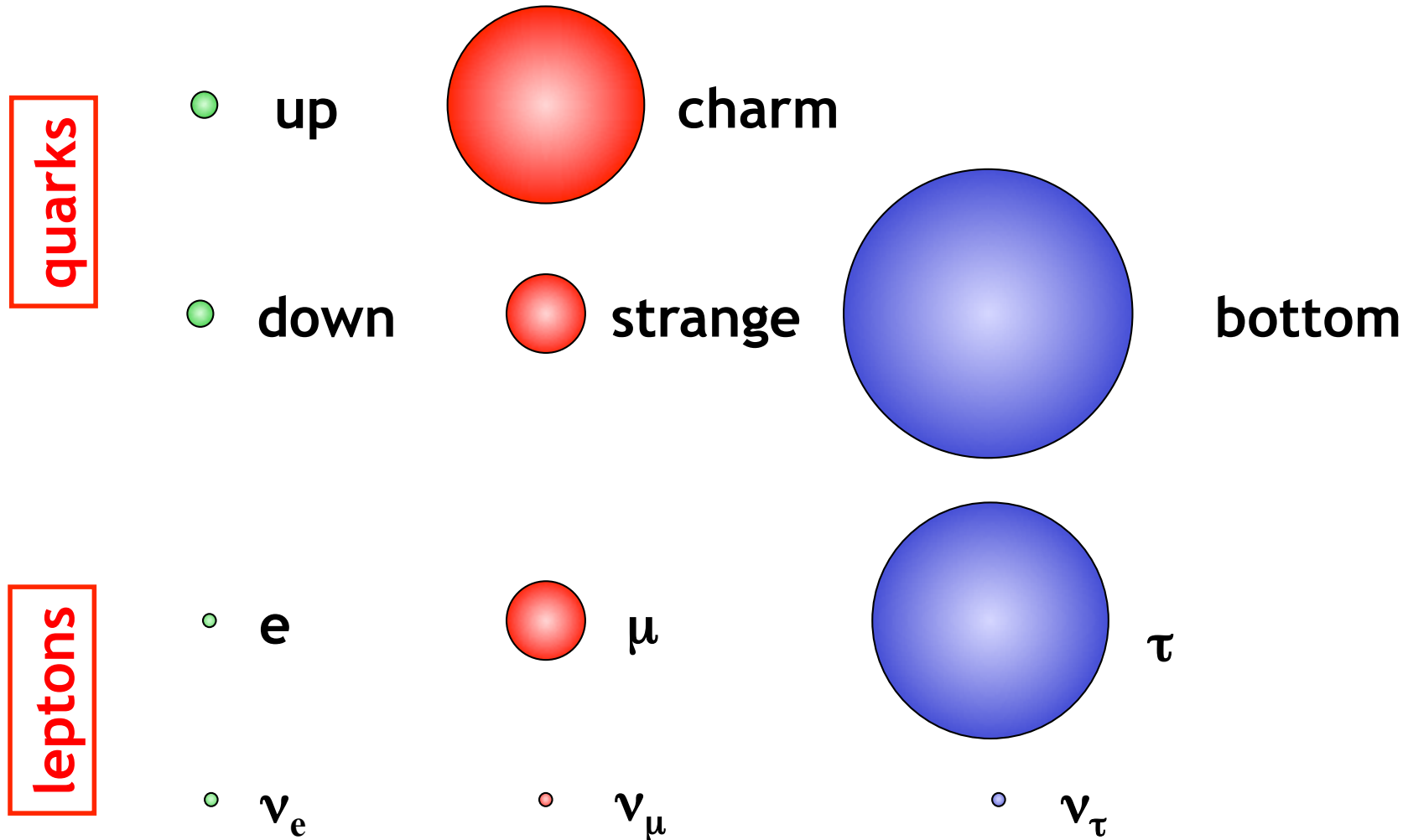
~ 10⁻⁸ ?

(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?

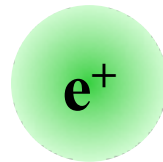
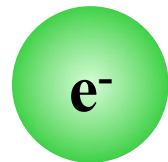
What about Antimatter?

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.

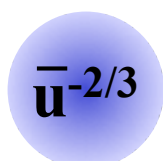


electron



positron

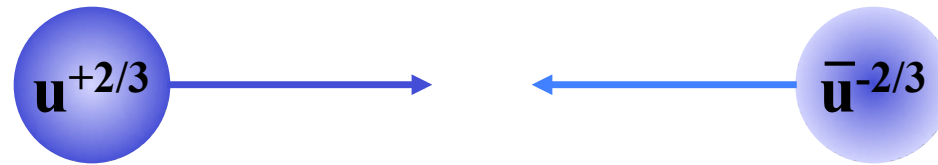
up quark



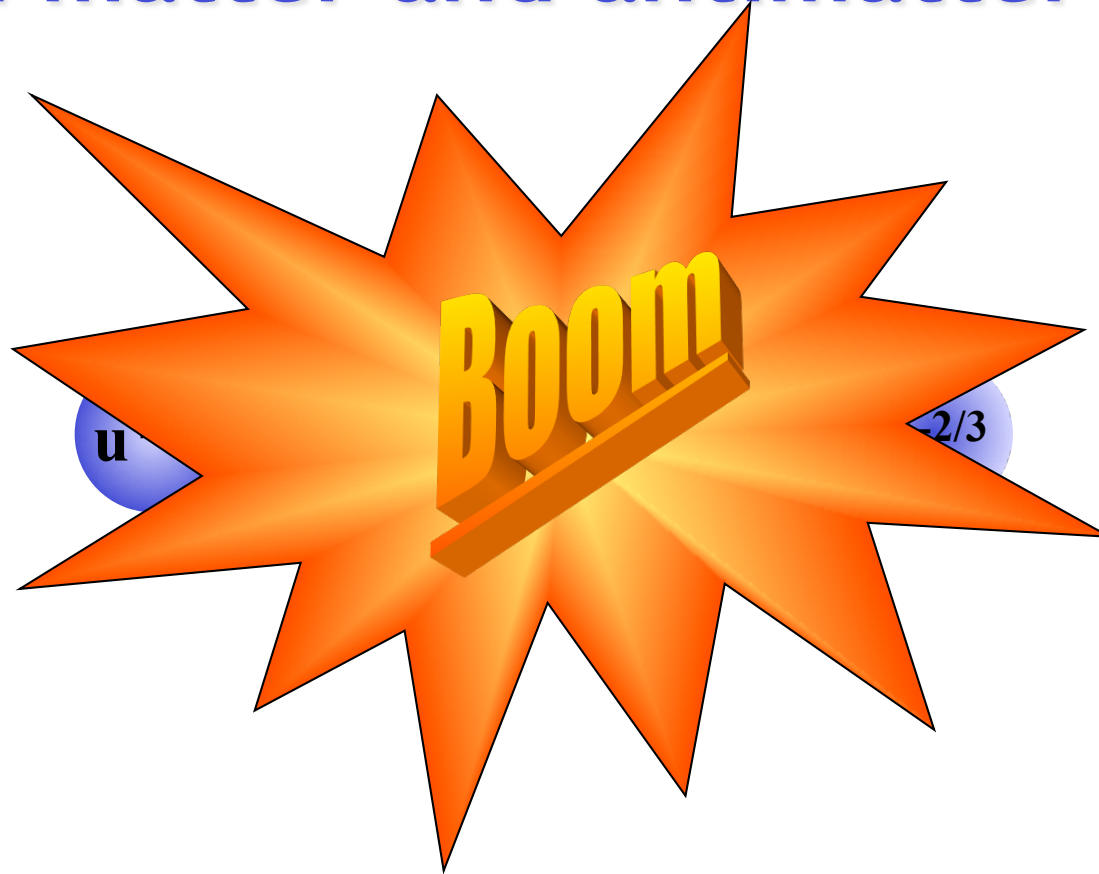
up anti-quark

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**


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

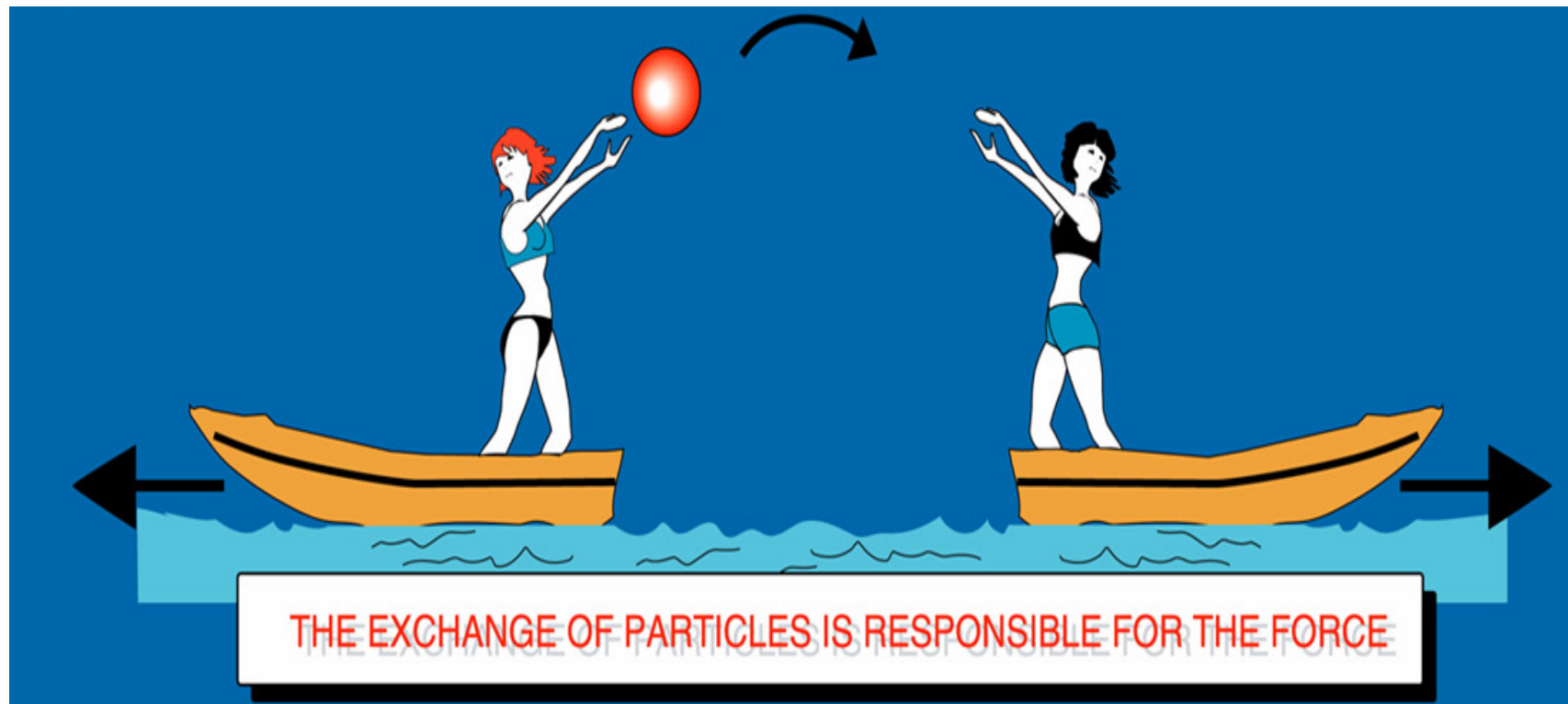
2) The **strong nuclear force** holds the quarks together in the protons and neutrons ... **so that they can't escape** ...


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

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

The Particle Physics view of Forces

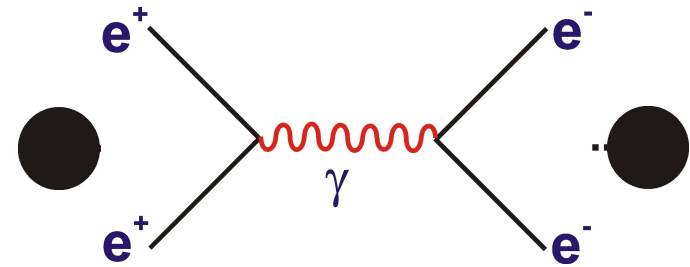
The microscopic view: forces also caused by particles ... being exchanged between the matter particles



The Force Carriers

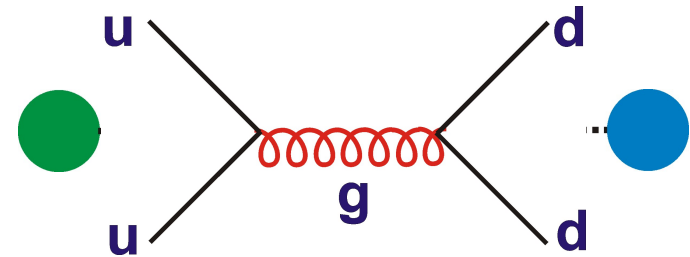
1) Electromagnetic force

PHOTON EXCHANGE



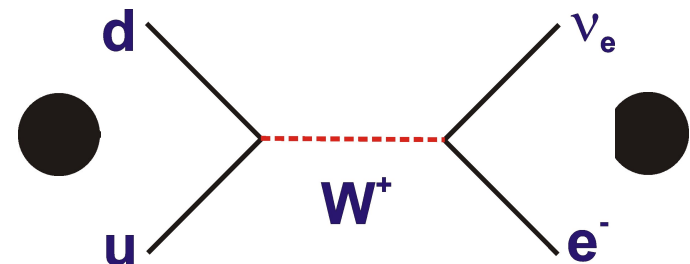
2) Strong nuclear force

GLUON EXCHANGE



3) Weak nuclear force

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

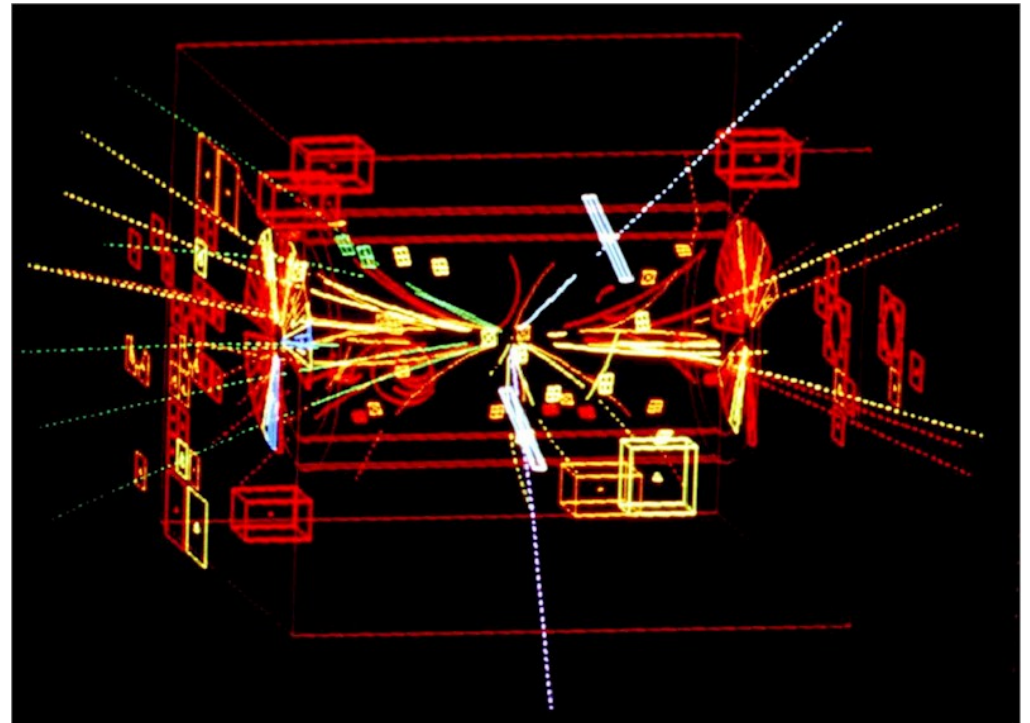


Short range because W and Z bosons are HEAVY:

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

W and Z bosons

Discovered in 1983 by the UA1 experiment, which included your host today!



The first ever observation of a Z^0 boson. It decayed to an electron and a positron (the white tracks)

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



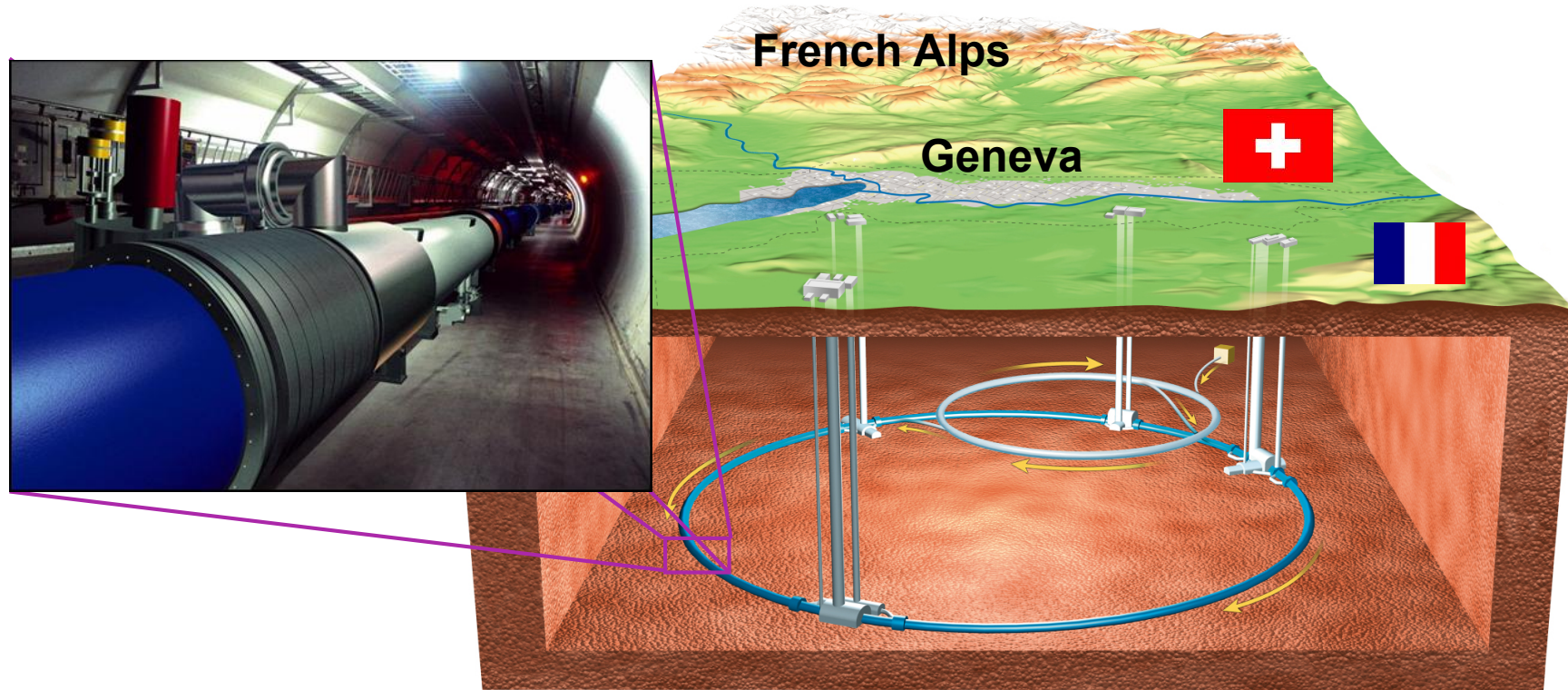
... near Lake Geneva,
between the Alps and the Jura



... is the world's largest Physics Laboratory



... what CERN is currently doing ...

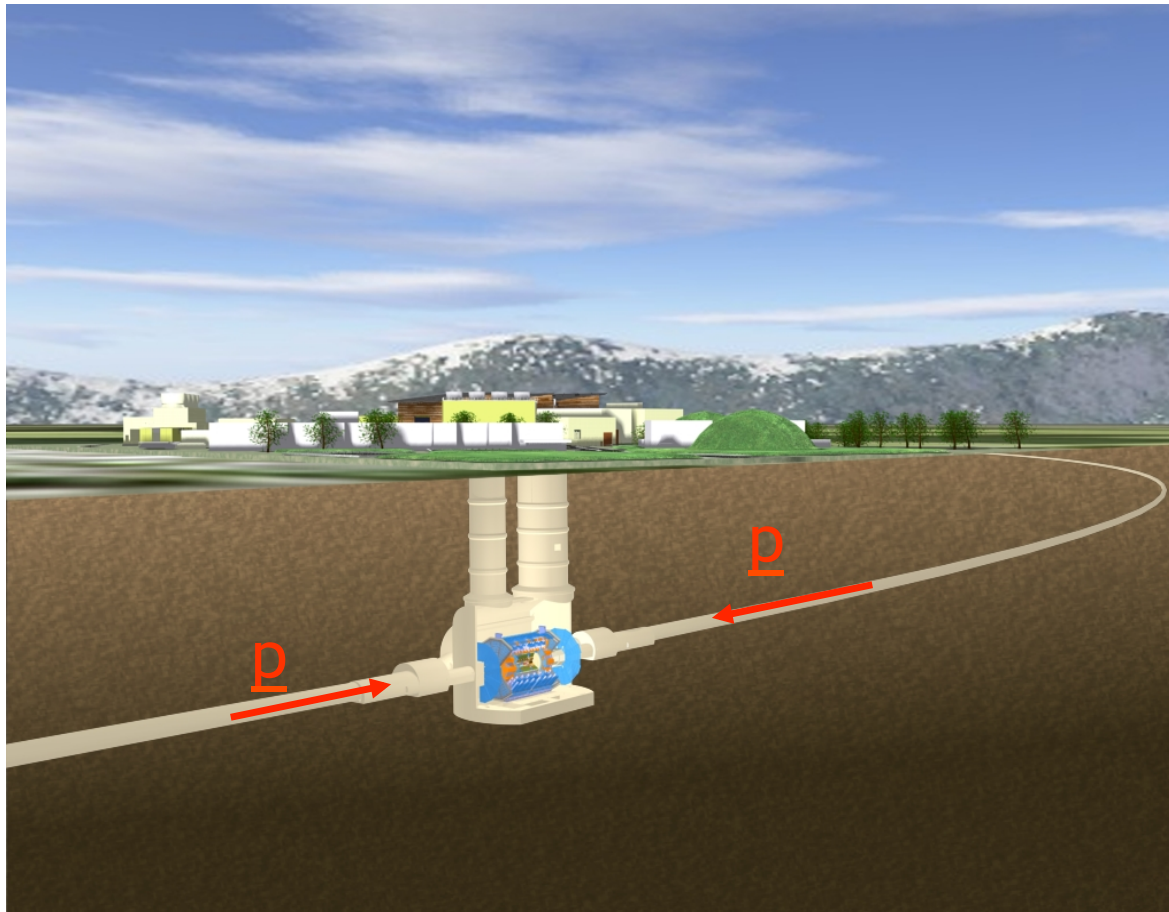
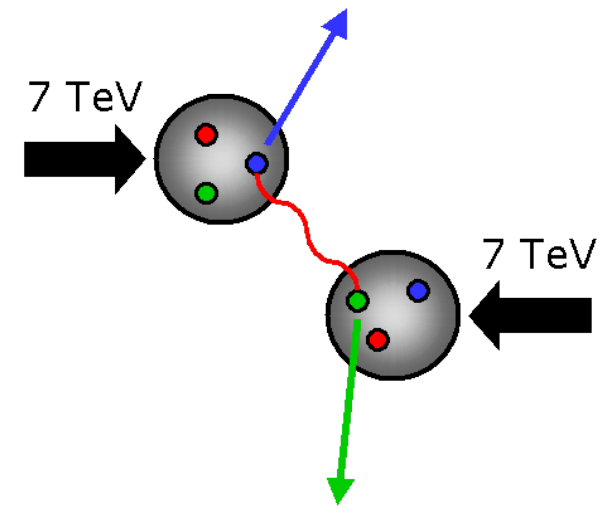


The Large Hadron Collider (LHC)

100m underground ... in a 27km long tunnel...
... accelerates protons to 0.9999999991 of the speed of light.

The Large Hadron Collider

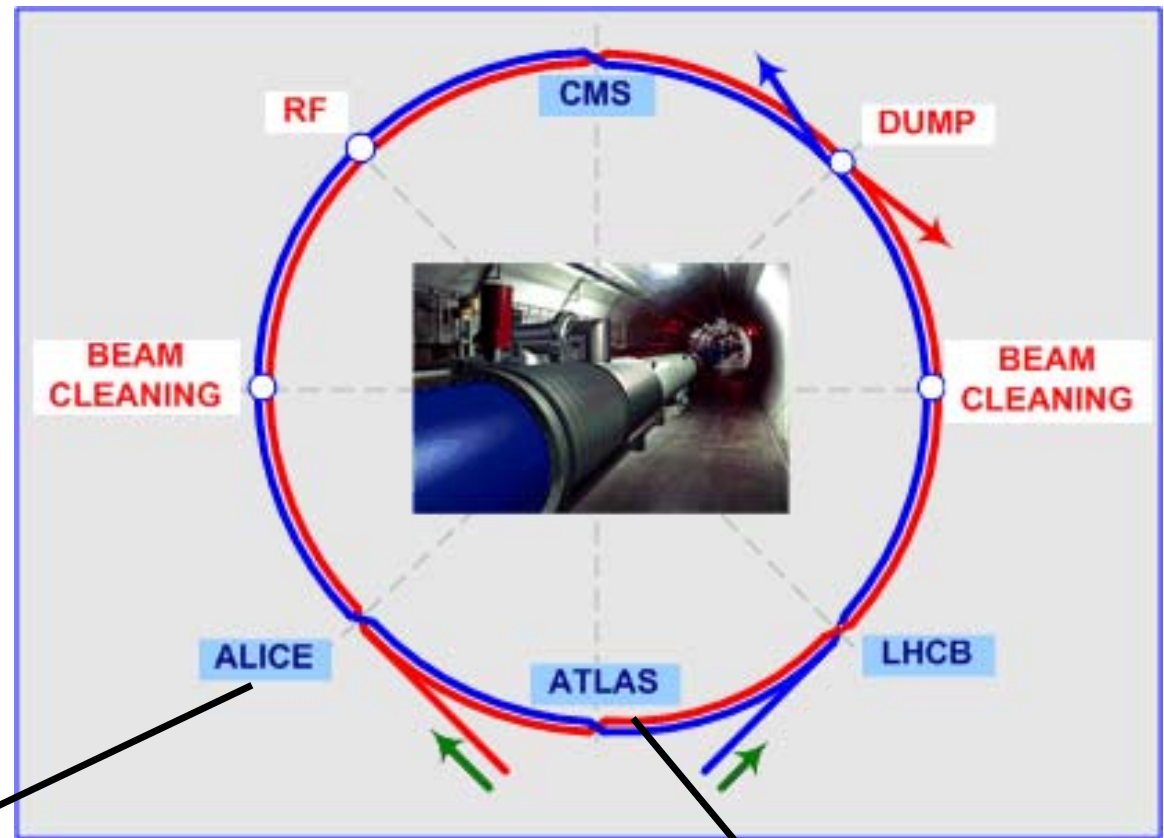
Colliding protons with 7 TeV each
($7 \times 10^{12} = 7$ trillion electron-volts)



- Each proton goes round ring 11,000 times per Second.
- 10^{11} protons per bunch
- 40 million bunch crossings per second
- Ring looks just 4m long to the protons!

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

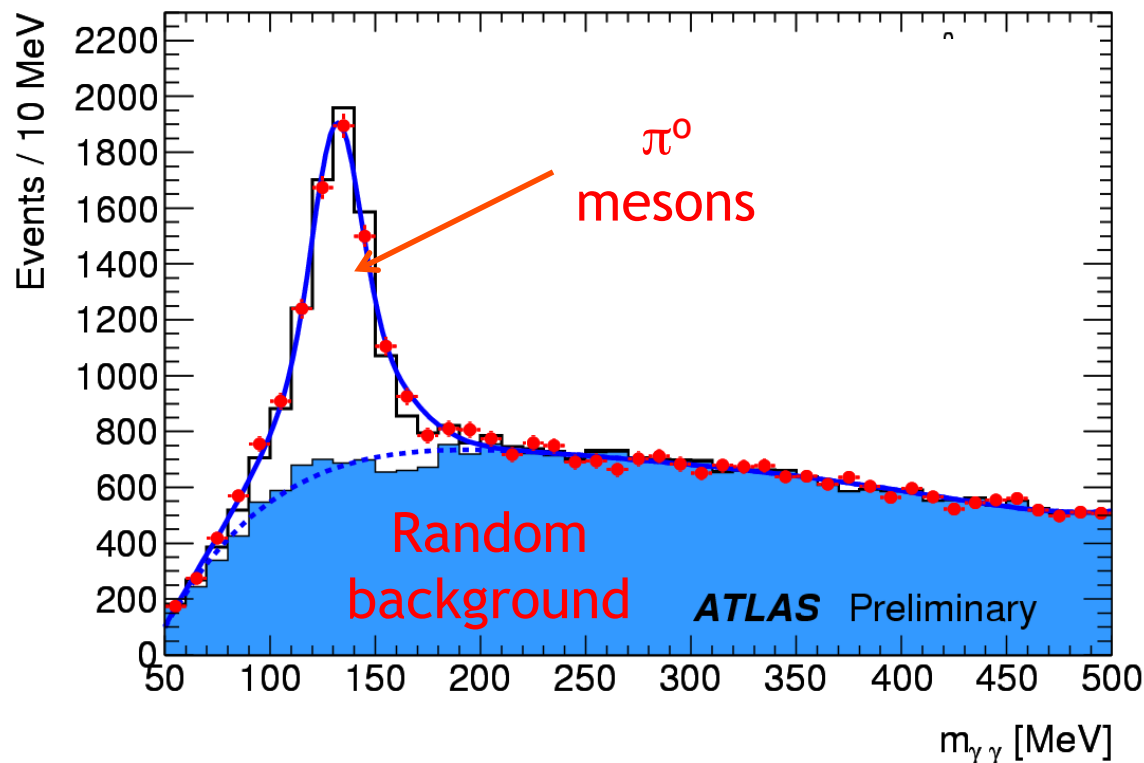


“Seeing” Particles at the LHC

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

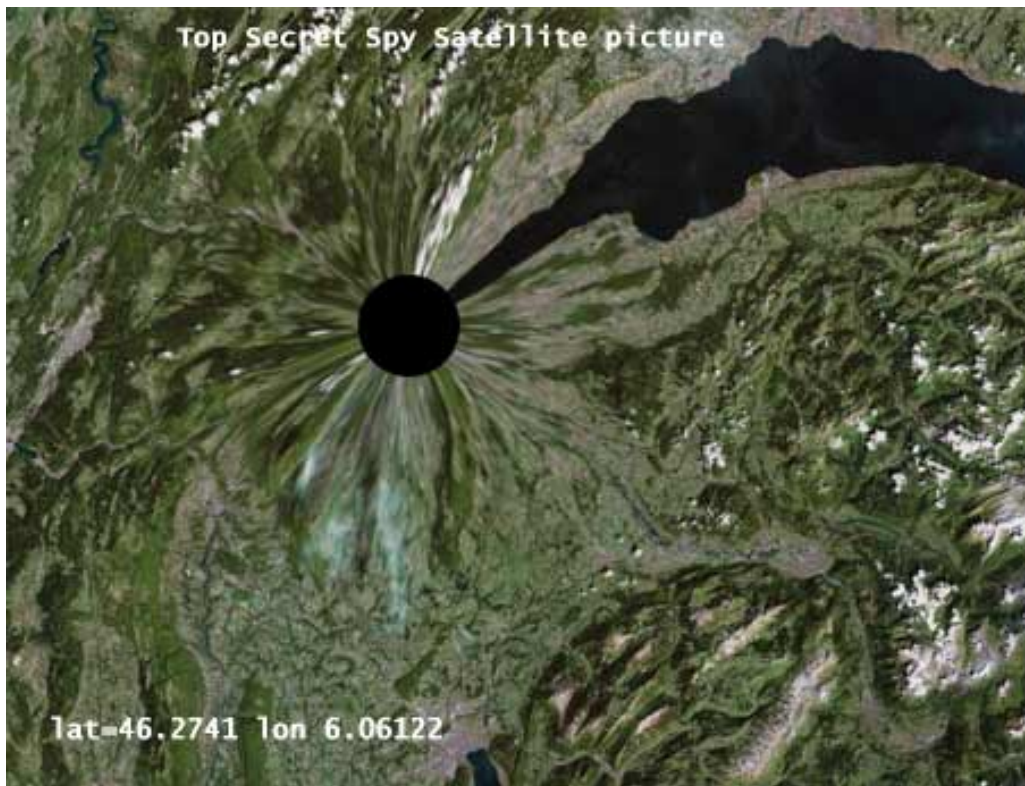
e.g. a π^0 hadron consists of $u\bar{u}$ or $d\bar{d}$ quarks

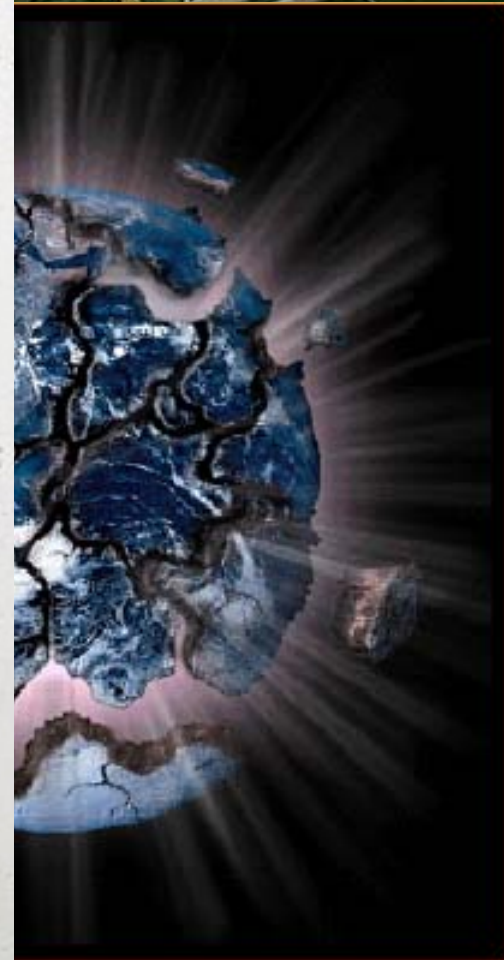
and decays fast to 2 photons $\pi^0 \rightarrow \gamma\gamma$

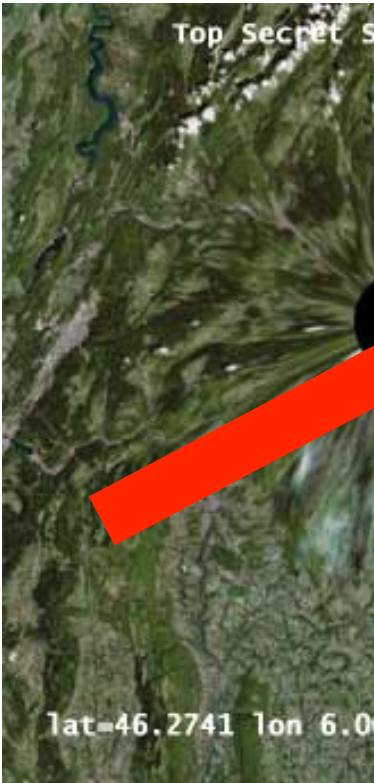


... combine all pairs of photons in every event
... look at what particle mass they combine to give ...

One of the first LHC plots!...

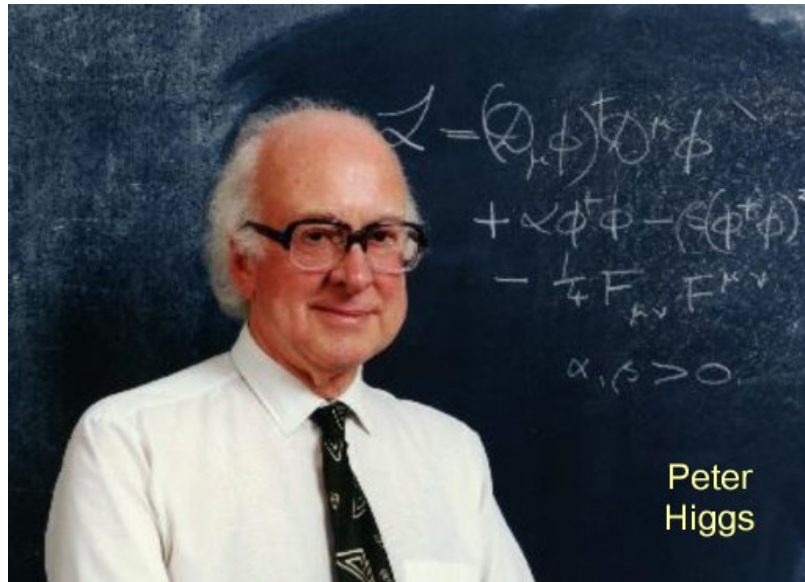






What might the LHC Discover?...

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

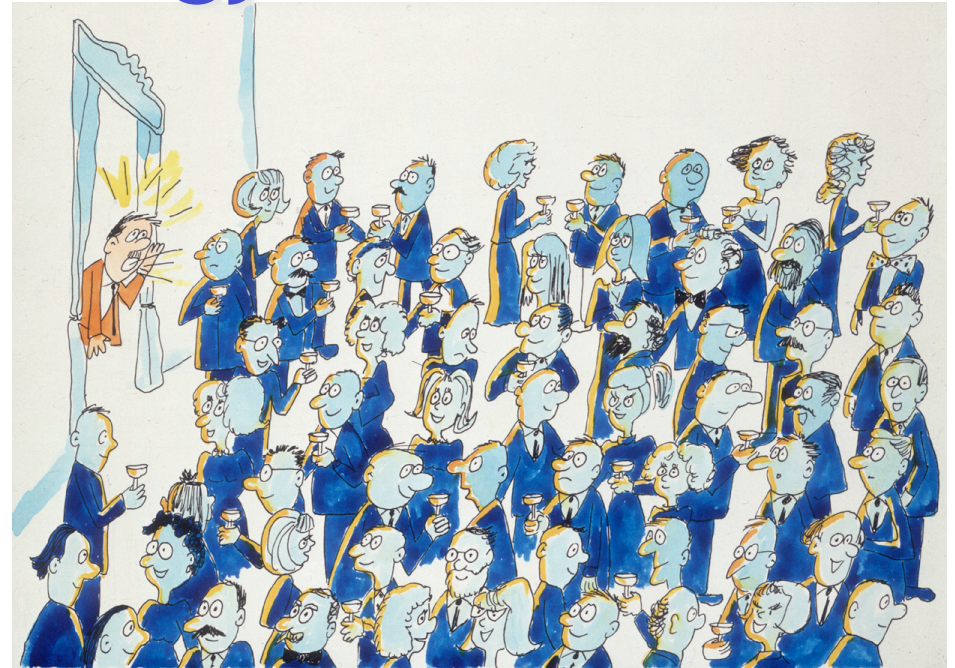


In the mid 1960s, British physicist Peter Higgs came up with a theory

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.

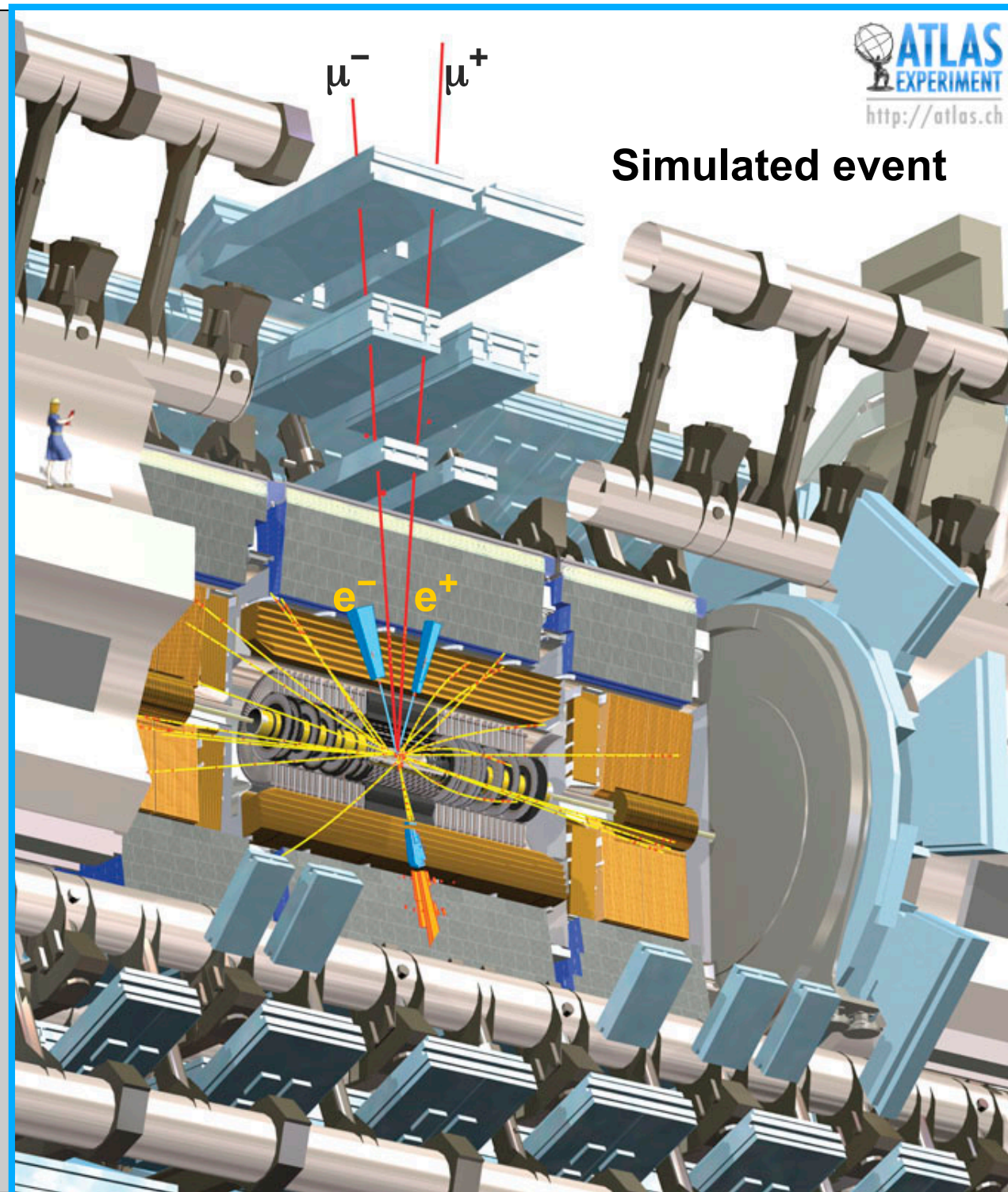
$$H \rightarrow Z + Z$$

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

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

1 billion events per second

1 Higgs produced every 10 seconds!



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% of design collision rate

• We should have an answer to the Higgs boson question in about 18 months ... but most new physics is extremely rare

• The LHC will run for 15-20 years ...

WATCH THIS SPACE!