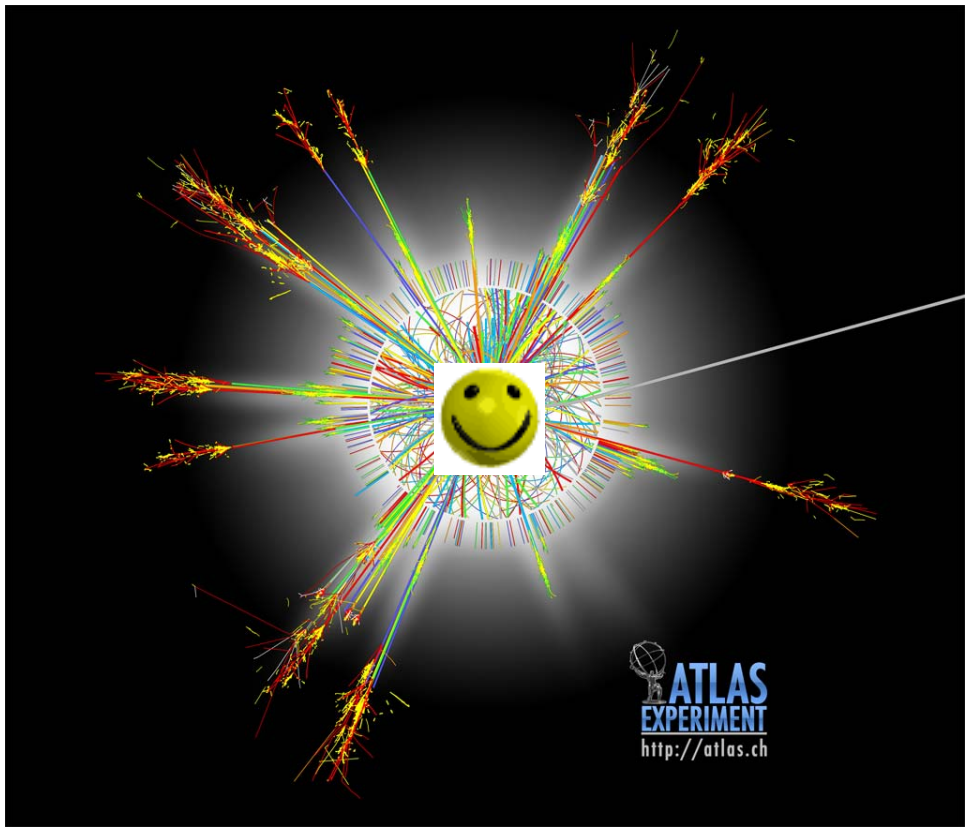
Particle Physics, Birmingham and the Large Hadron Collider

Paul Newman

UNIVERSITY OF BIRMINGHAM



London Expert Lectures
23 June 2010

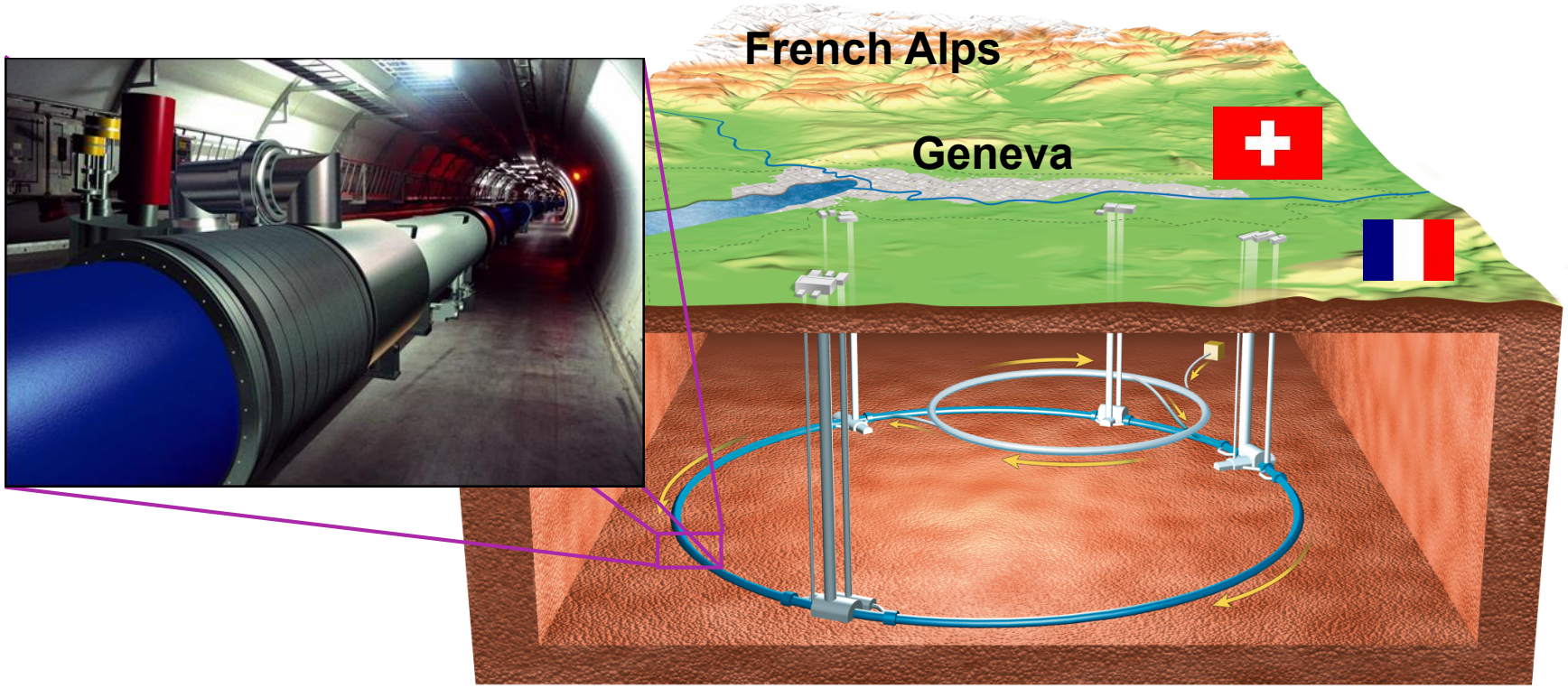
On the Swiss French Border …

… near Lake Geneva, between the Alps and the Jura

… is the world's largest Physics Laboratory

CERN

… what CERN is currently doing …



The Large Hadron Collider (LHC)

100m underground, CERN has built the world's largest machine in a 27km long tunnel.
… it will accelerate protons and lead ions to 0.999999991 of the speed of light.

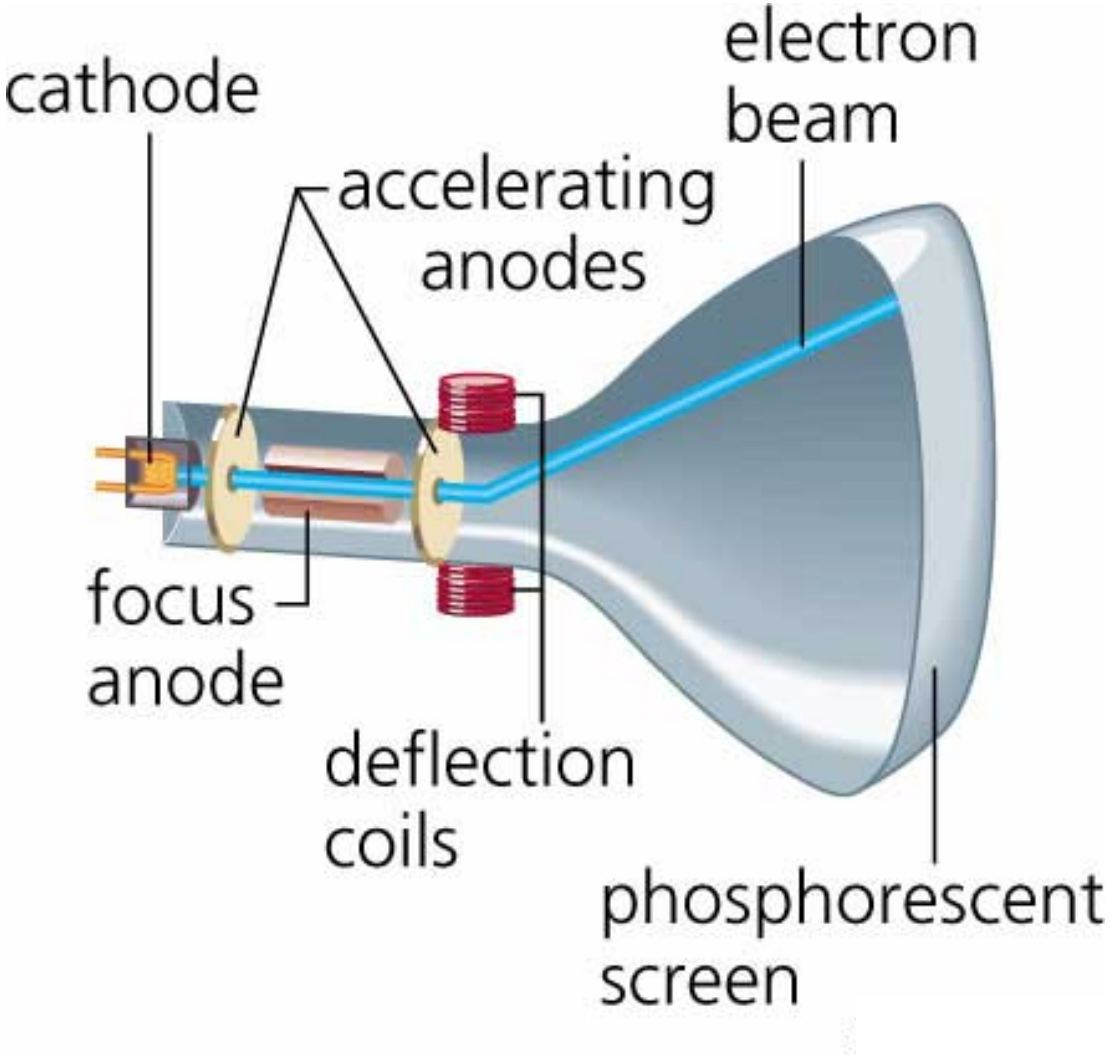
Your (granny's) TV is an Electron Accelerator!

- Particle physics accelerators are not so different …

- A particle of charge q accelerating through a potential difference V acquires a kinetic energy E=qV.

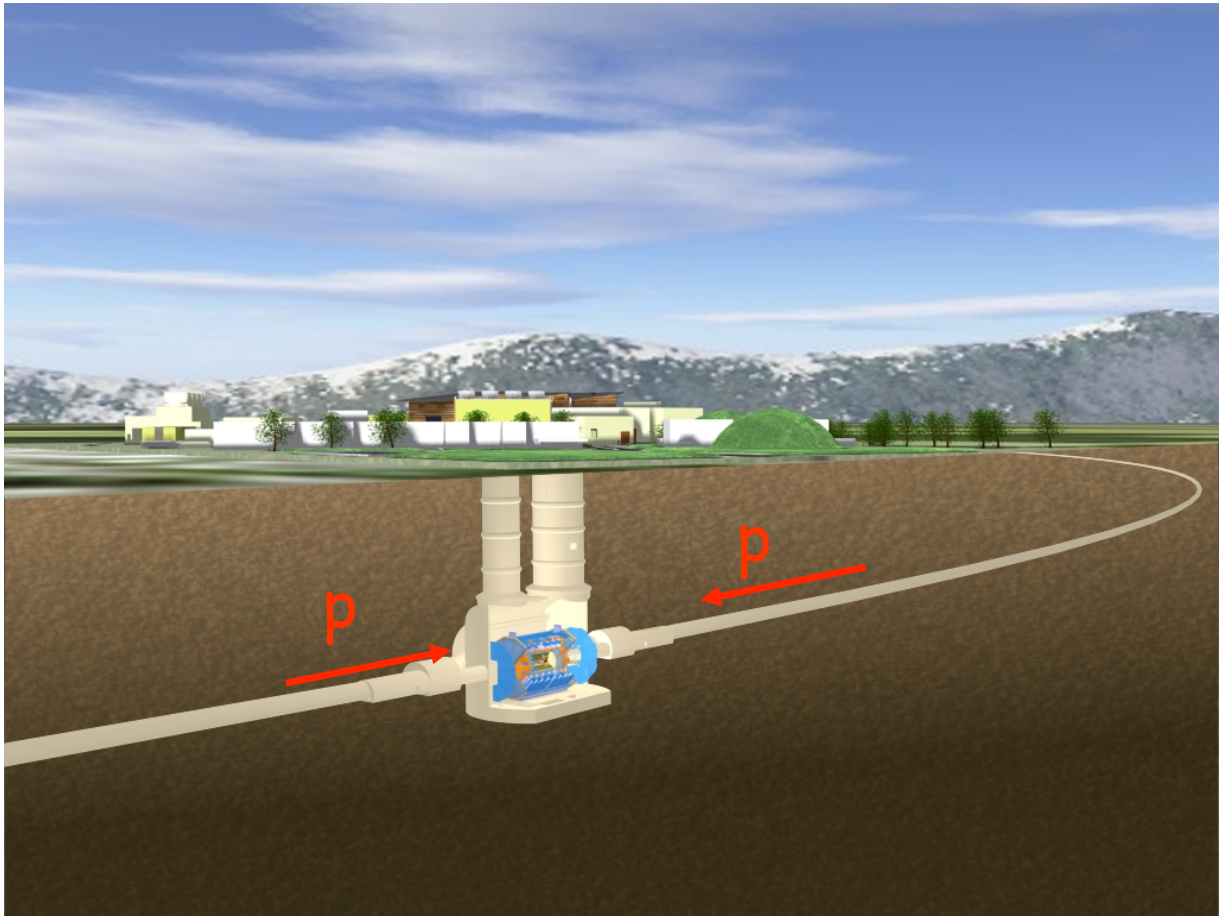
1 volt gives an energy of 1eV

- A TV accelerates electrons to 20 keV



- The LHC will accelerate protons to 7×10^{12} eV (=7 TeV!)

Some facts about the Proton Beams



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

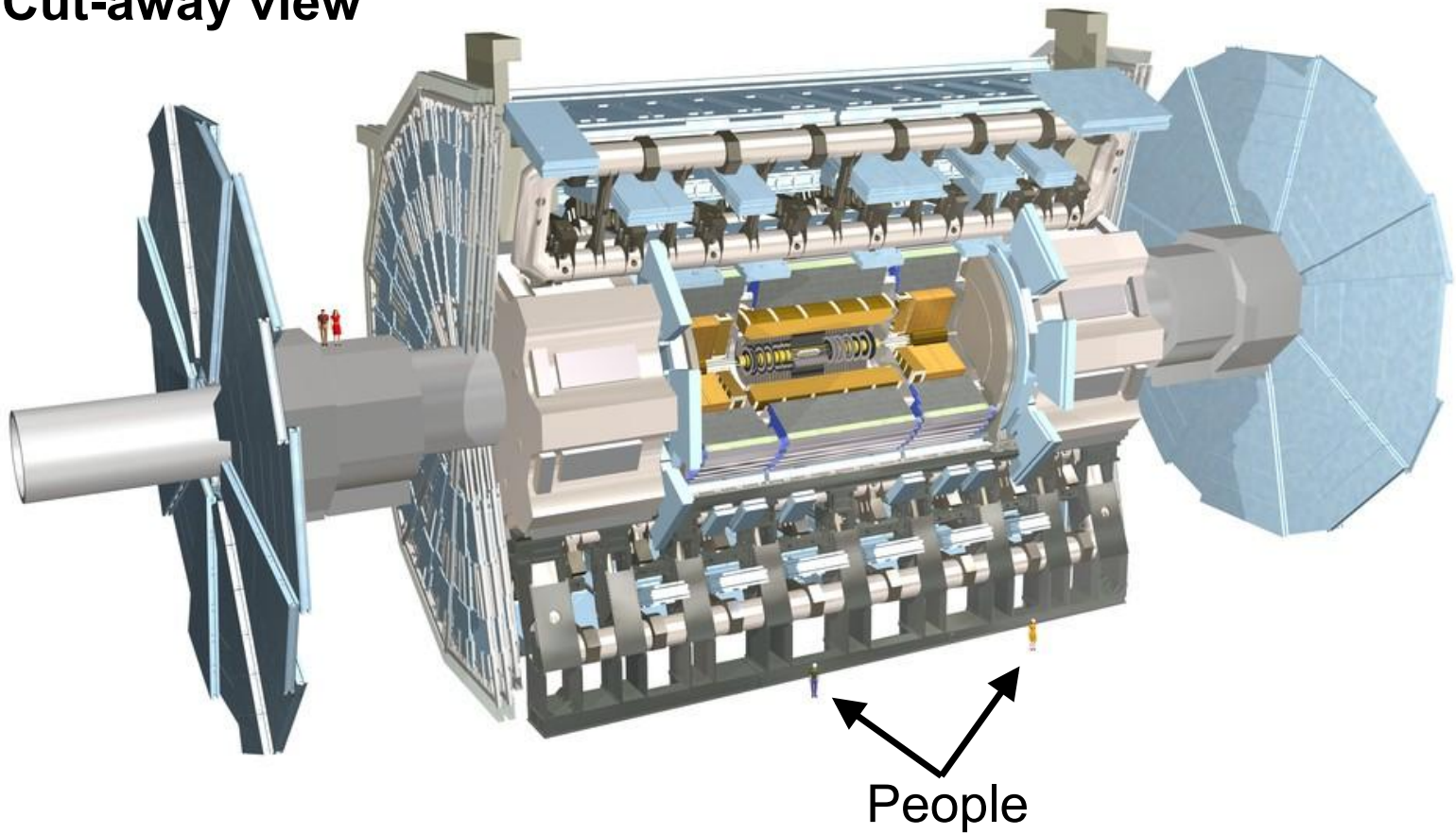
- Total energy of beam > 300 MJ (= family car at 1000 mph!)

- Due to the extreme effects of relativity, the ring looks just 4m long to the protons

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.

Detecting the Results of the Collisions

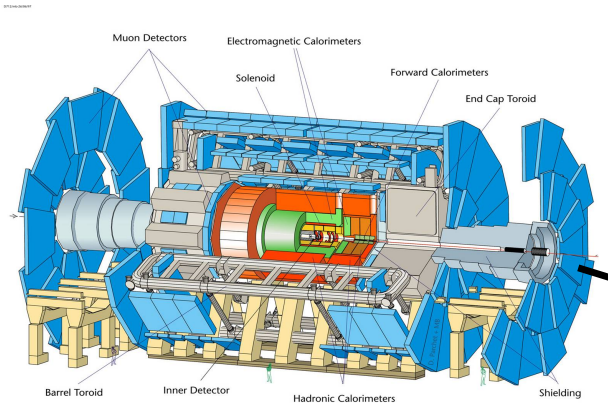
Cut-away view



Huge particle detectors will be needed to observe the results of the collisions … a bit like a giant camera …

… and there will be around a billion collisions in each detector per second!

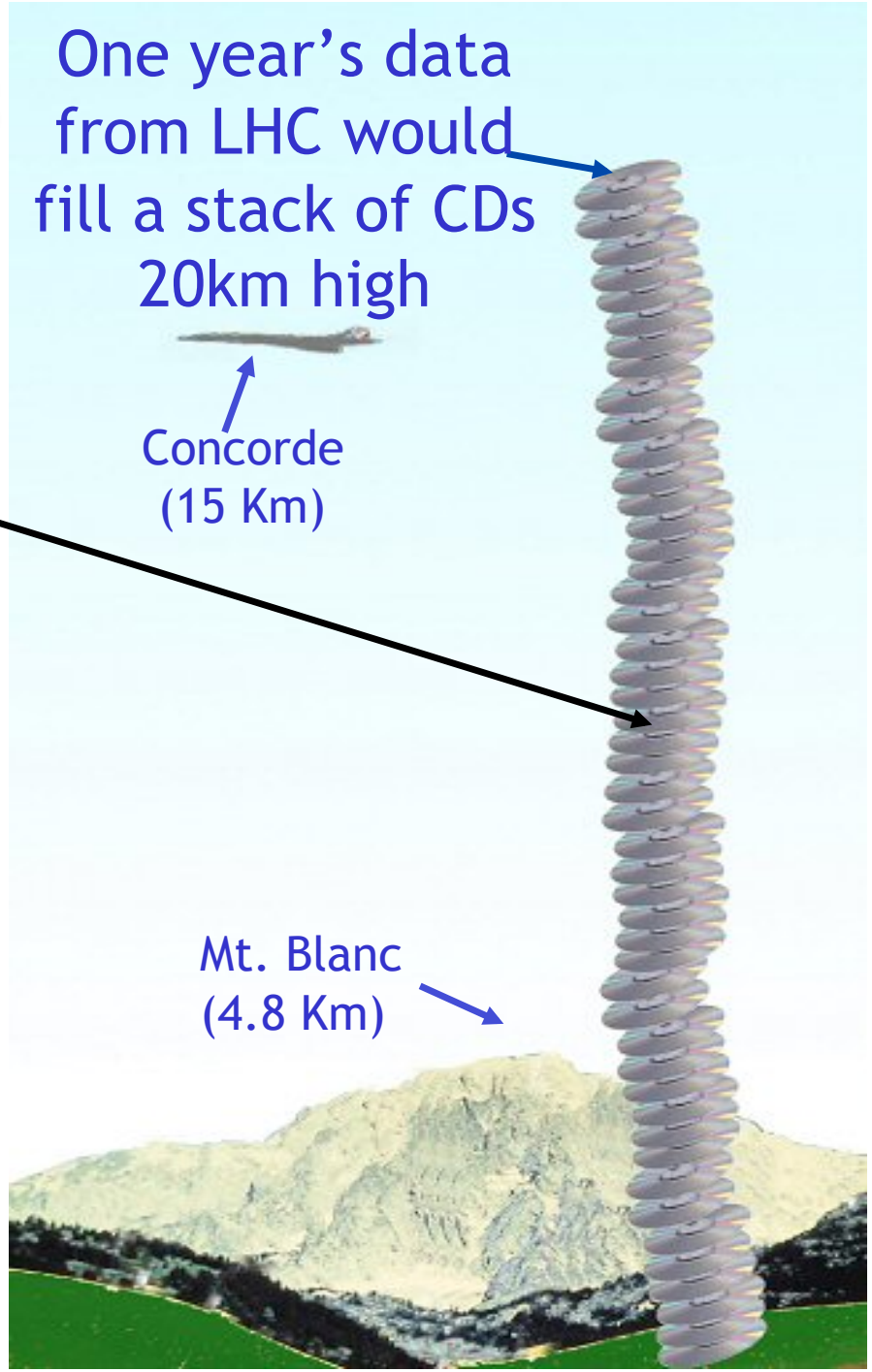
LHC Data Challenges



- Select about 100 most interesting events per second from 1 billion collisions

- Collect all data from the experiment and write it on disk

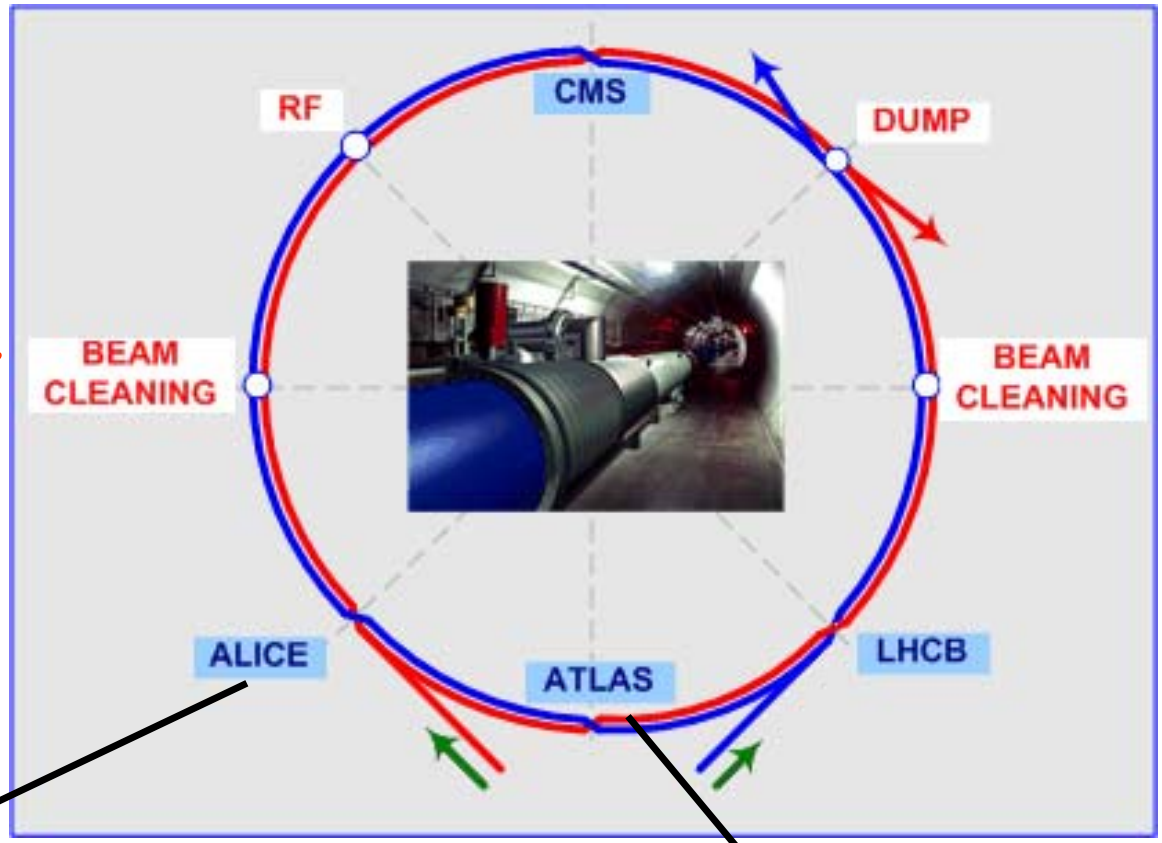
- Have the detector ready to find the next event!



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

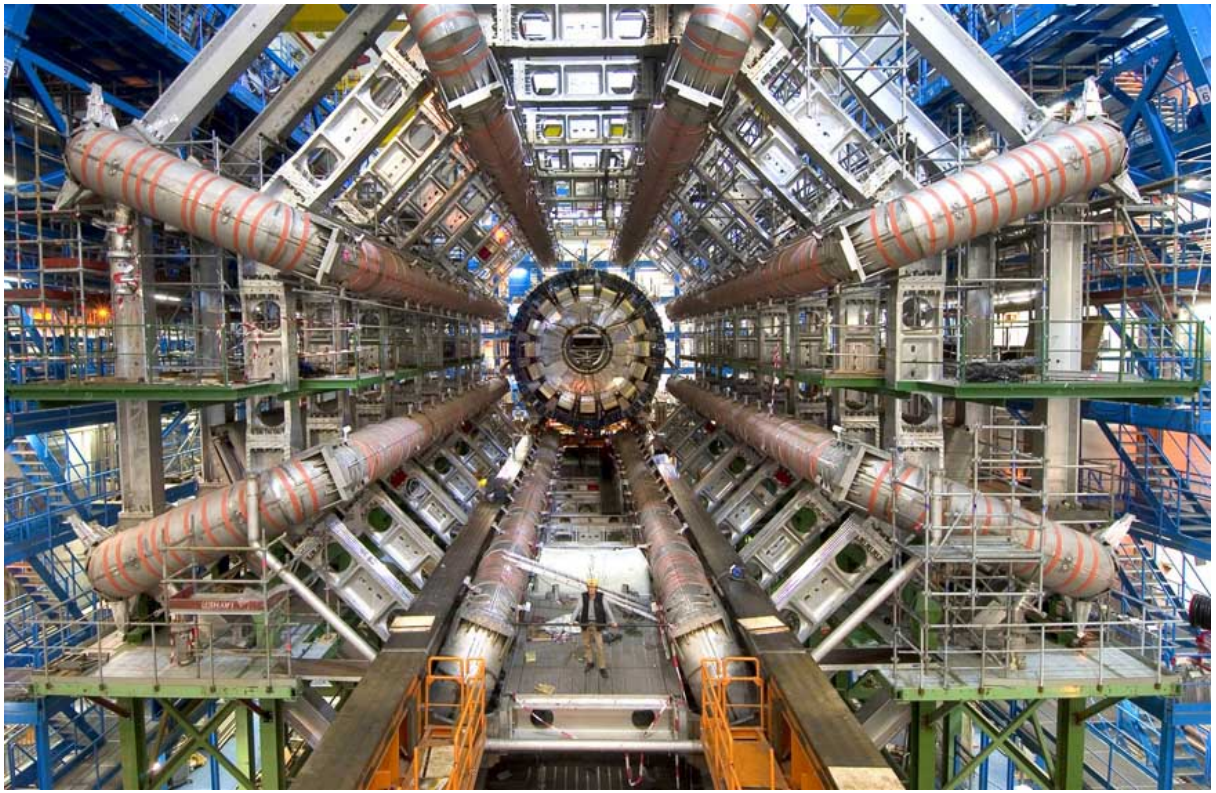
Birmingham & the LHC

Birmingham has two large groups, playing important roles in two of the four LHC experiments, ALICE and ALTAS

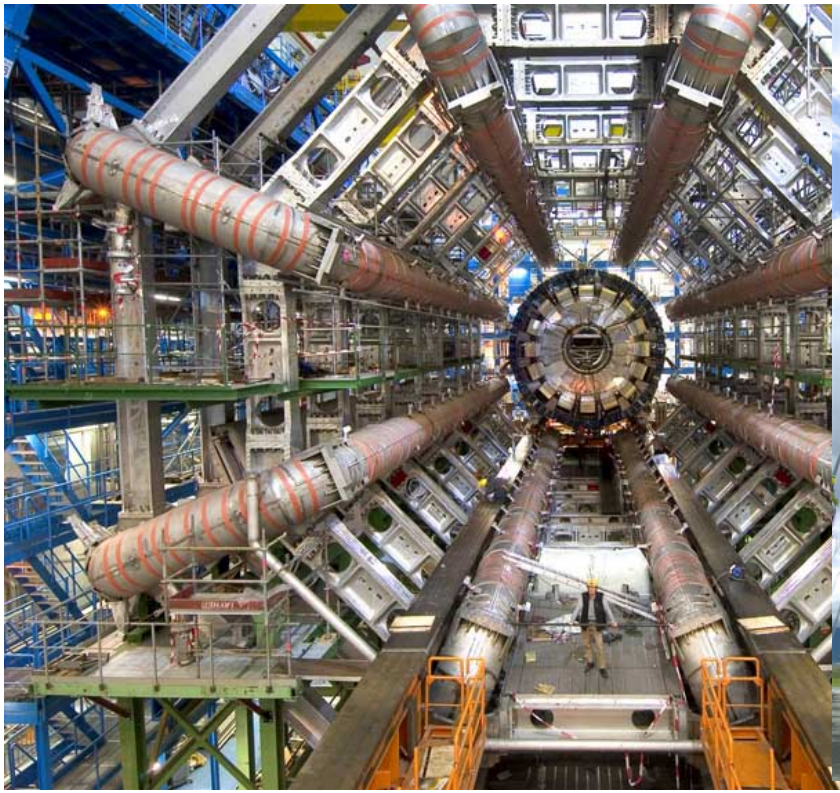


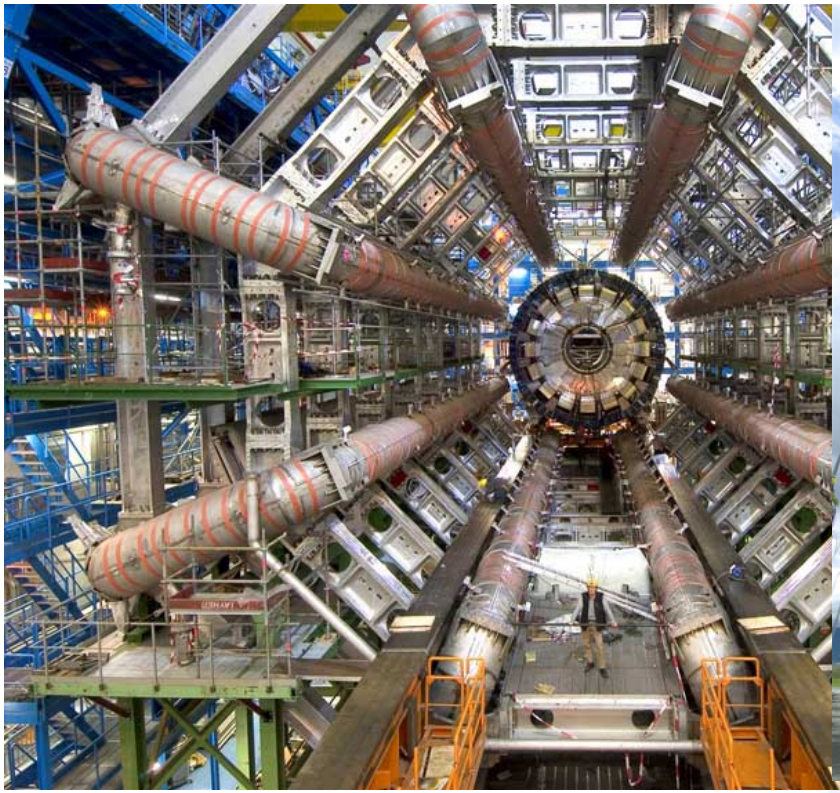
David Evans, UK ALICE Spokesman

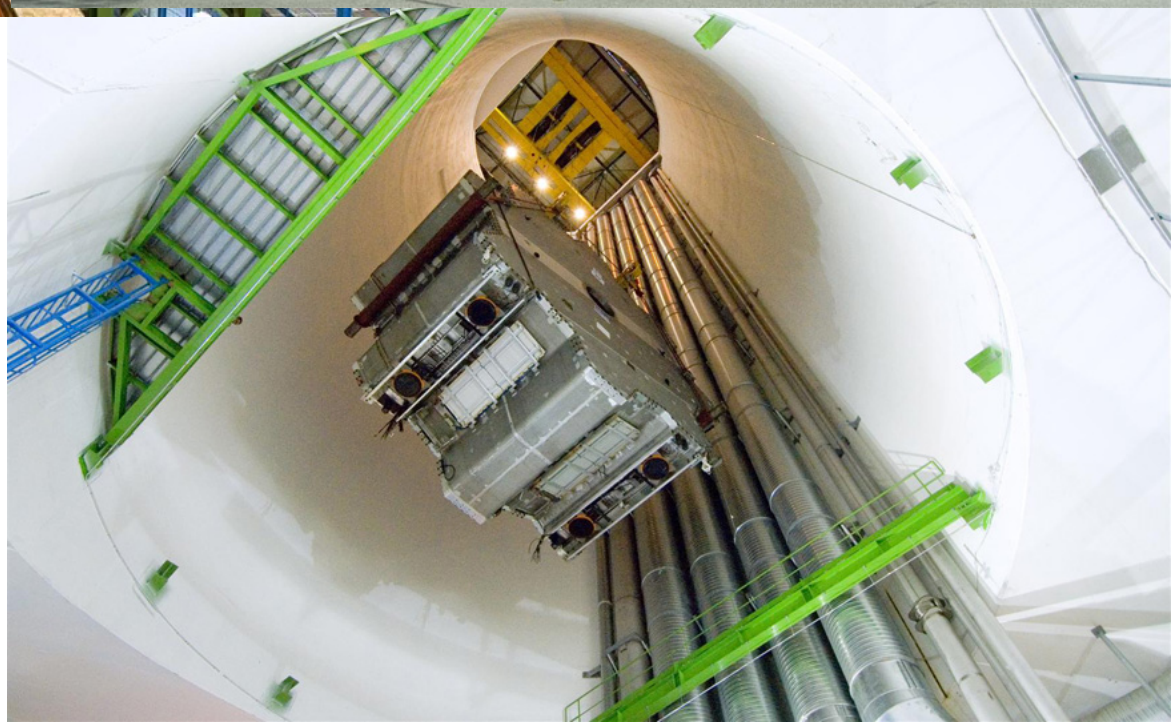
Dave Charlton, ATLAS Deputy Spokesman

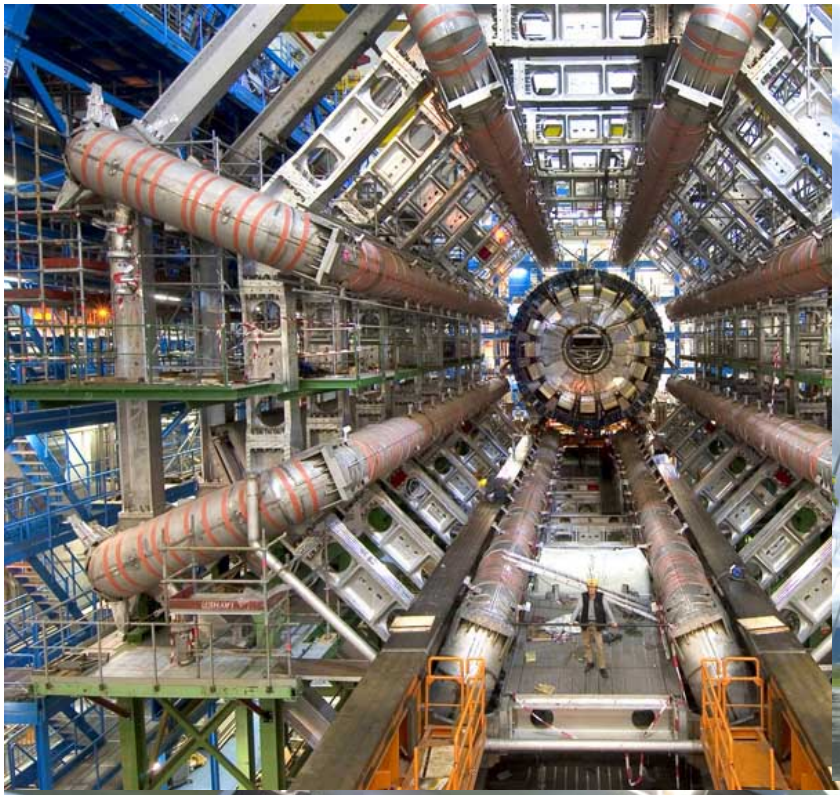


Building ATLAS







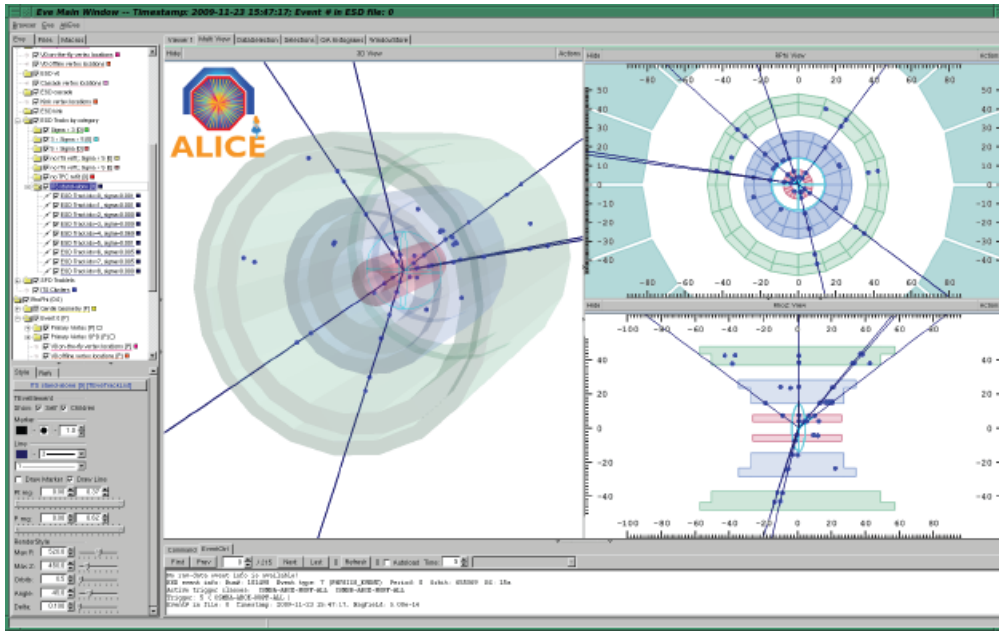


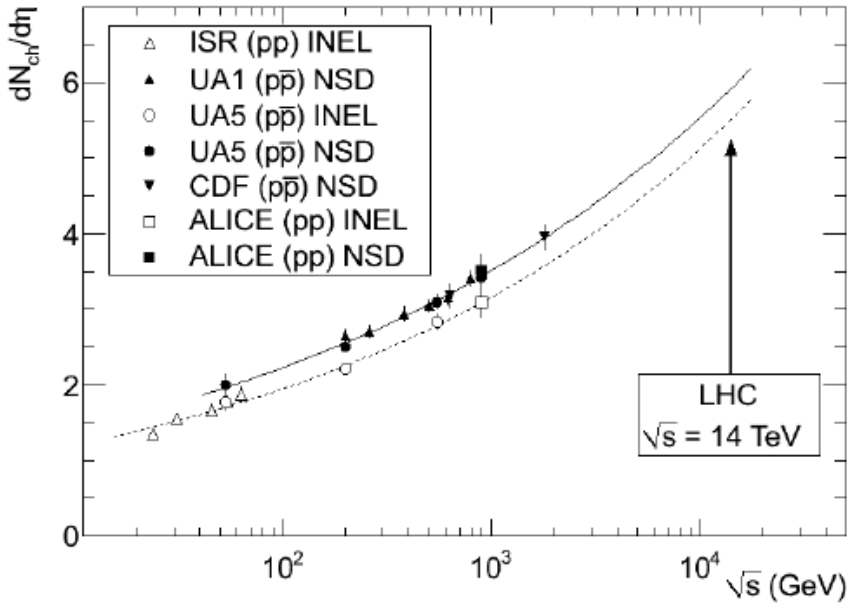
After some initial hiccups, LHC has been running well since late 2009 ☺

The First LHC Physics Paper …

First proton–proton collisions at the LHC as observed with the ALICE detector: measurement of the charged-particle pseudorapidity density at $\sqrt{s} = 900$ GeV

ALICE collaboration





… based on just 200 events

… published 6 days after the first collisions!

… but what's the point?

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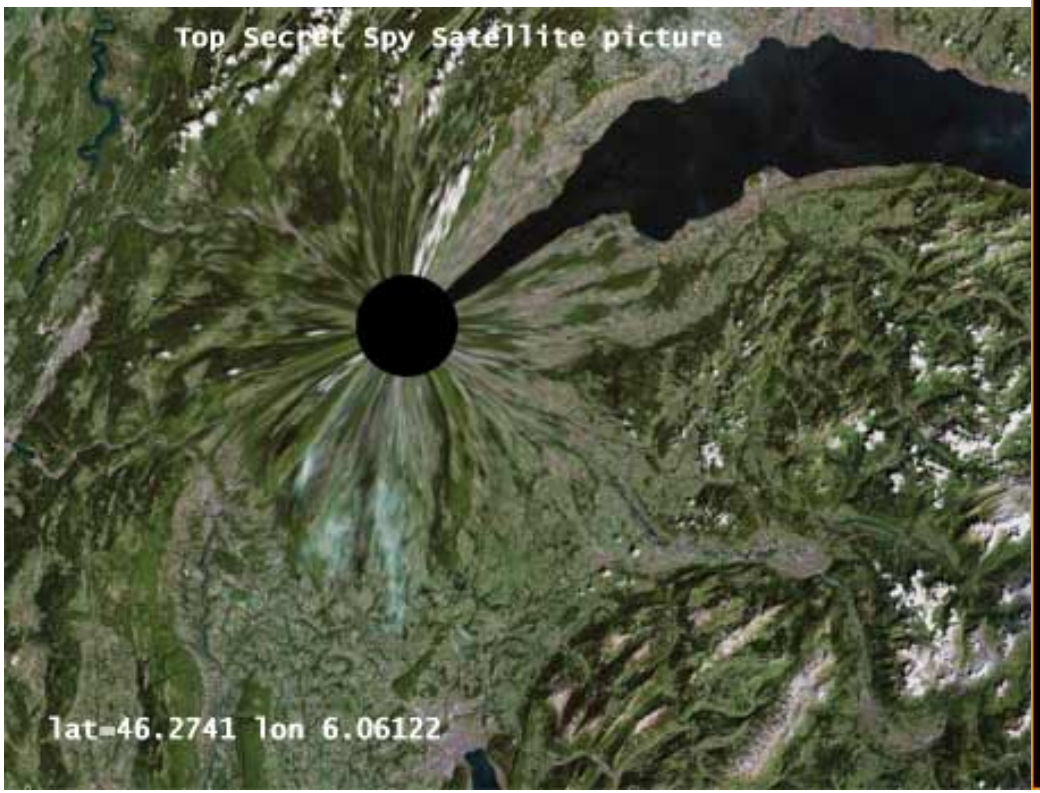
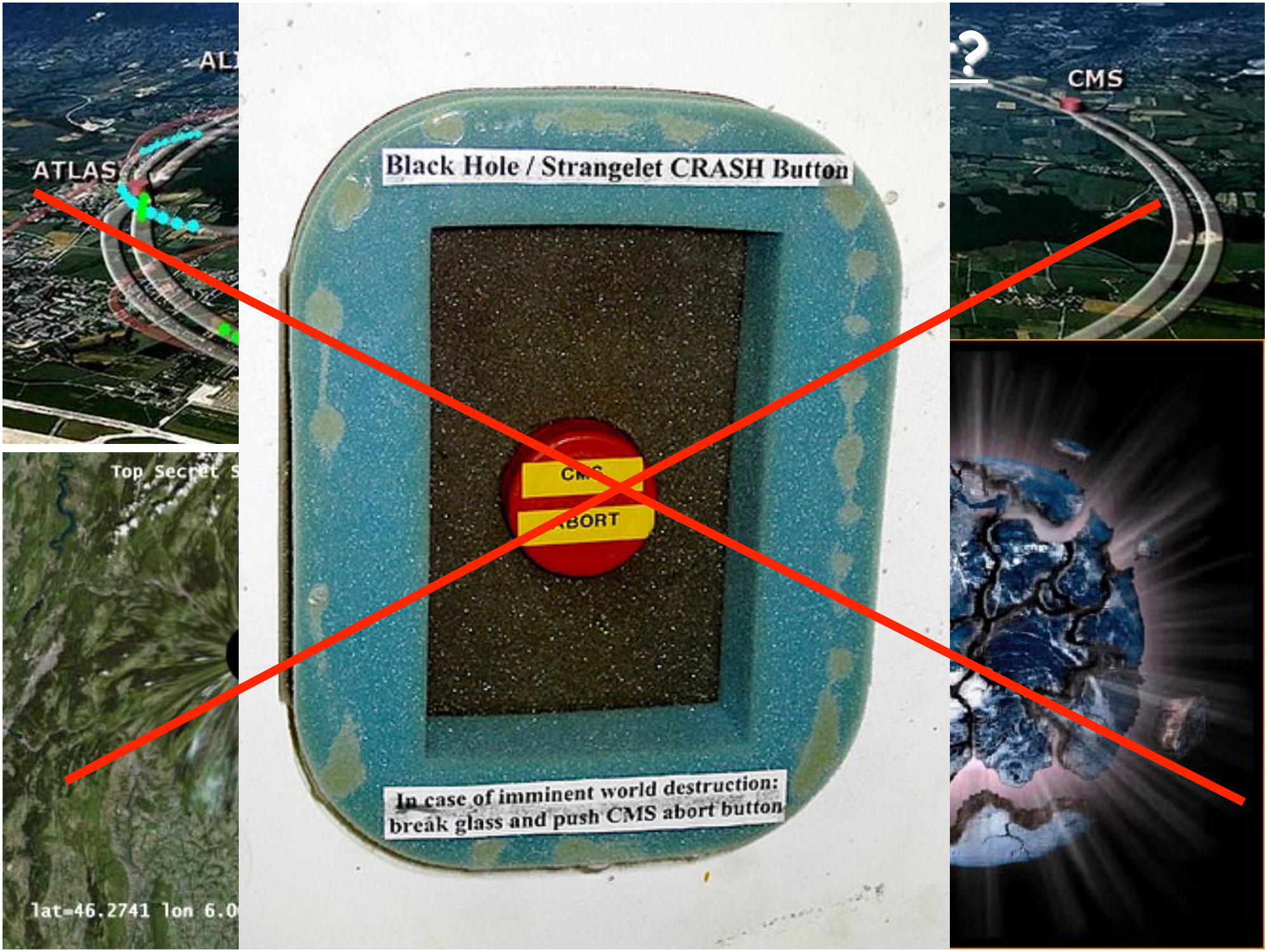



ATLAS
CMS
Top Secret
lat=46.2741 lon 6.0
Black Hole / Strangelet CRASH Button
CMS
ABORT
In case of imminent world destruction:
break glass and push CMS abort button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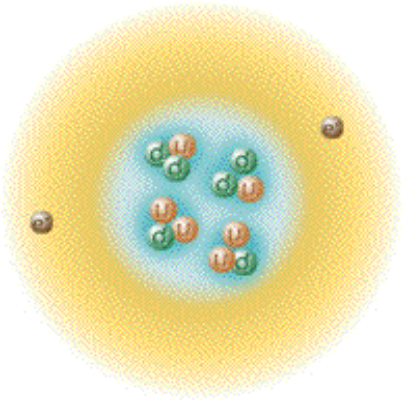
What is 'Stuff' Made of?

What is 'Stuff' Made of?

- All matter around us is made of atoms.
- Atoms consist of a positive nucleus (containing 99.98% of the atom's mass) and a cloud of electrons.



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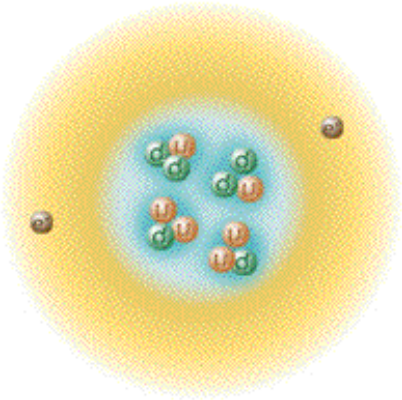
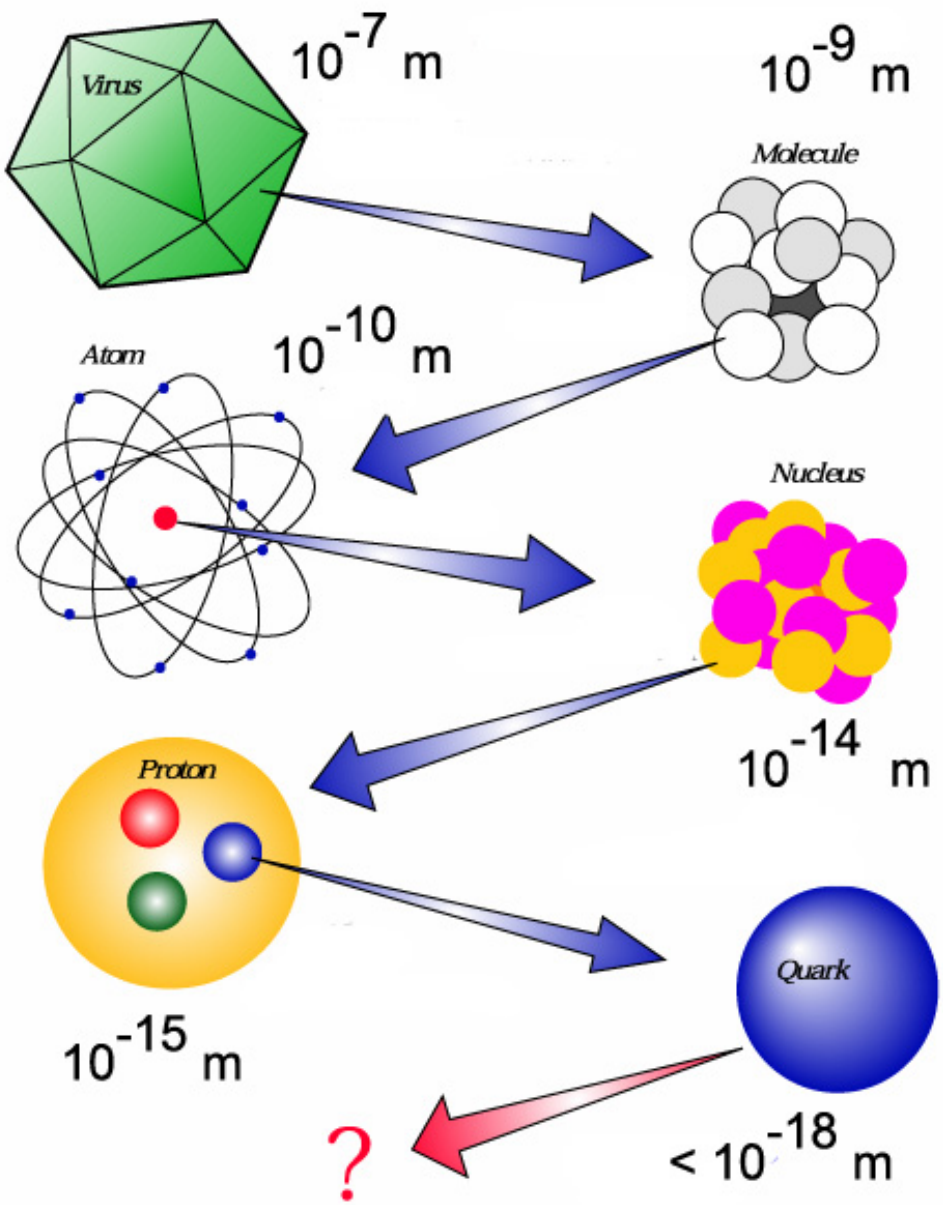


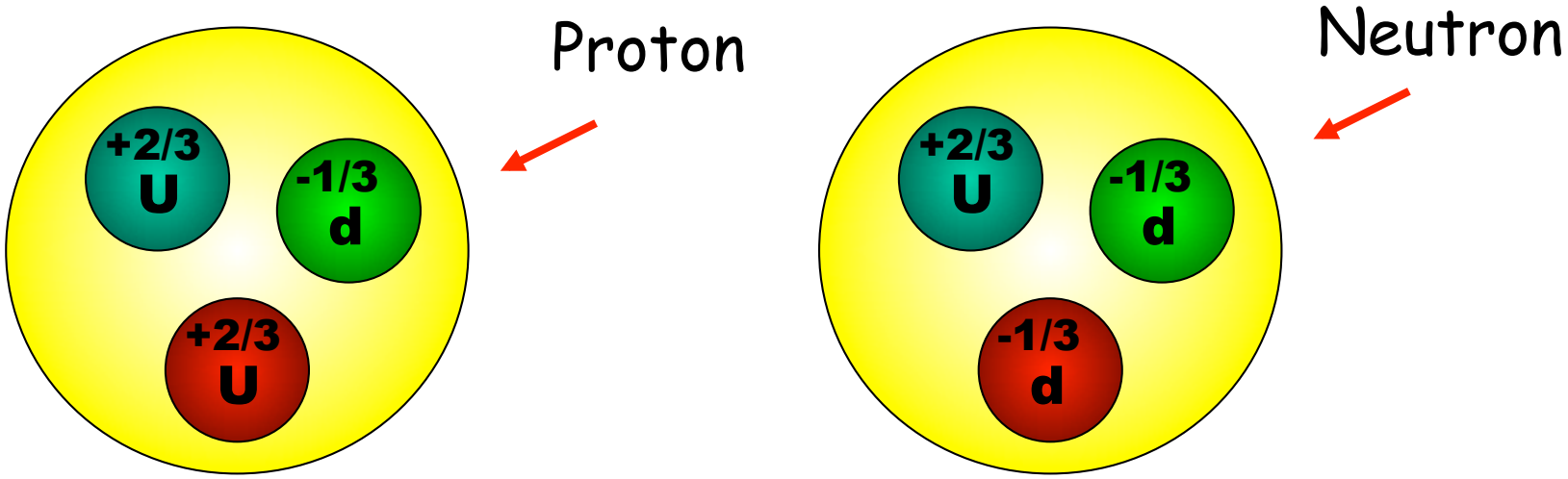
- Nuclei consist of protons and neutrons.
- The protons and neutrons are made of quarks.



The Quark Building Blocks

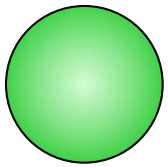
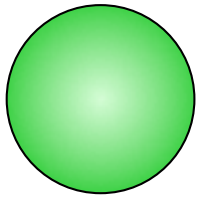
- Protons and neutrons are made from two types of quarks: Up (u) and Down (d).

- u-quarks have electric charge +2/3 while d-quarks have charge –1/3 (in units of the electron charge)



Family of Particles

So, there is 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 up of these four particles.

… but nature has other ideas …

quarks

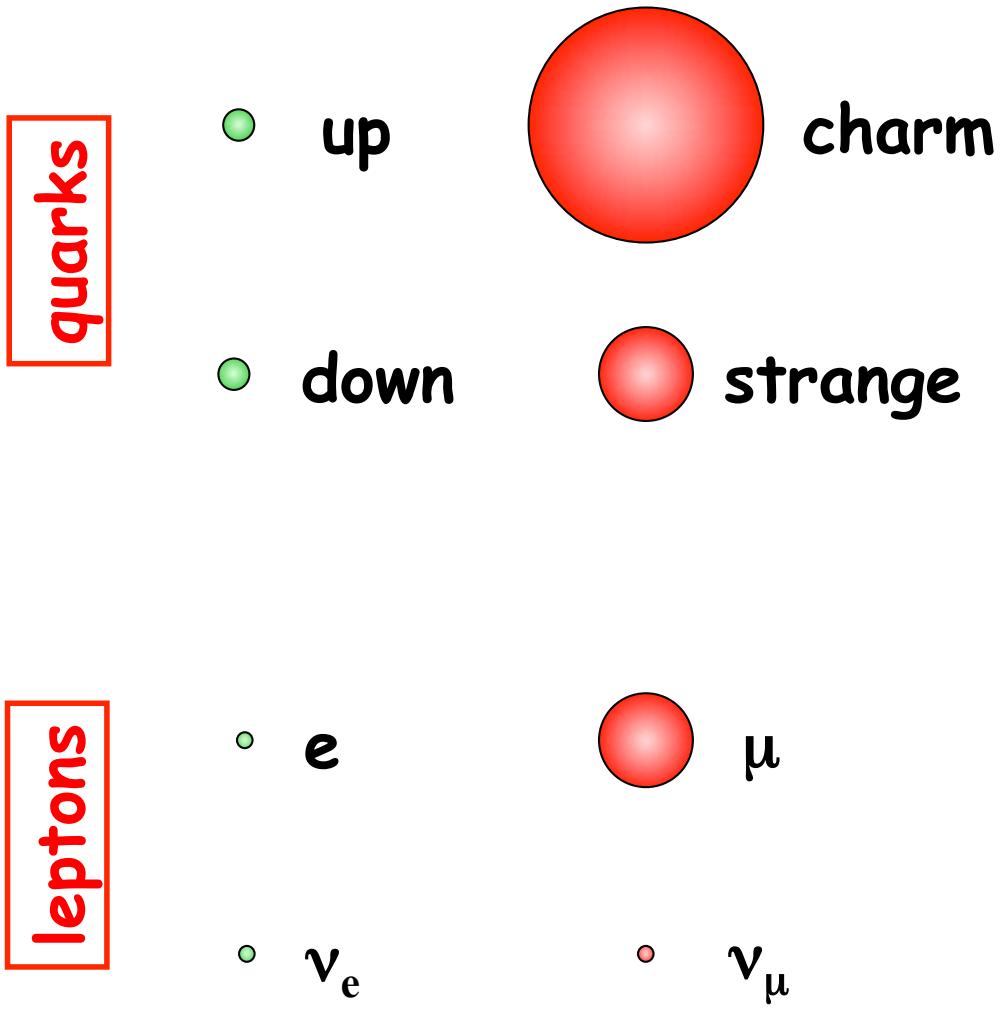
- up
- down

leptons

- e
- ν_e

… but nature has other ideas …

Nature supplies us with two extra families that are very much heavier:



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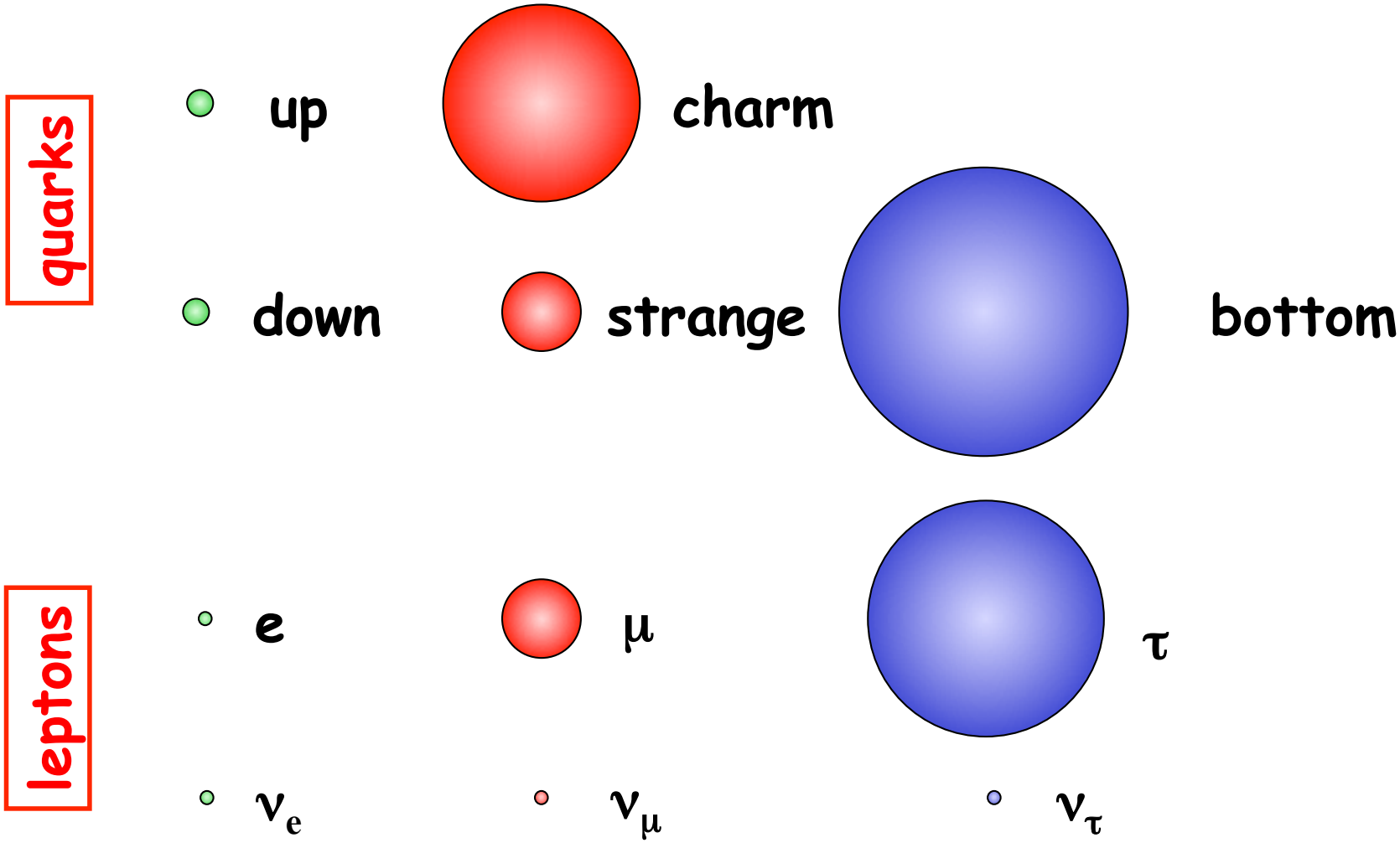
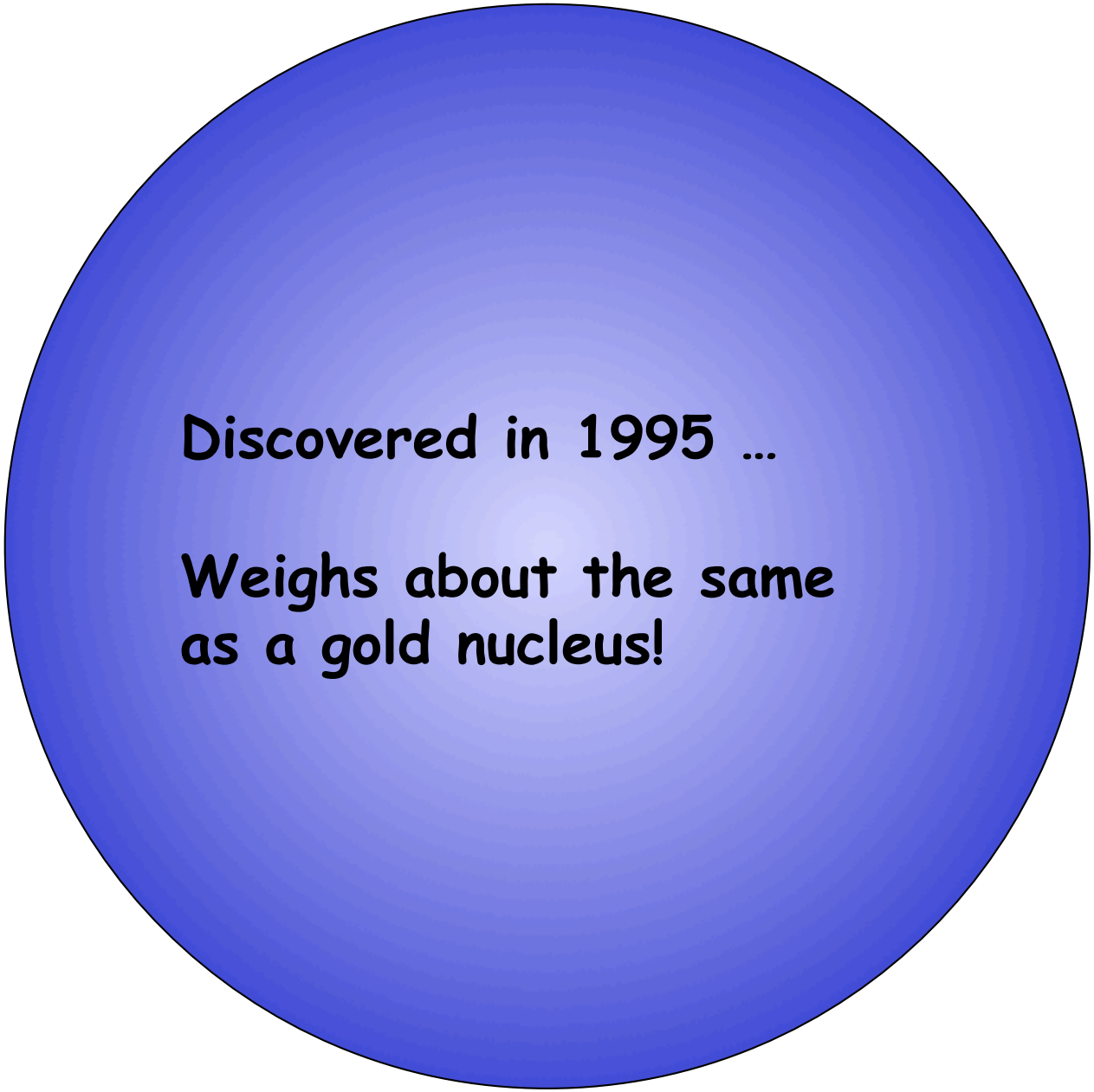
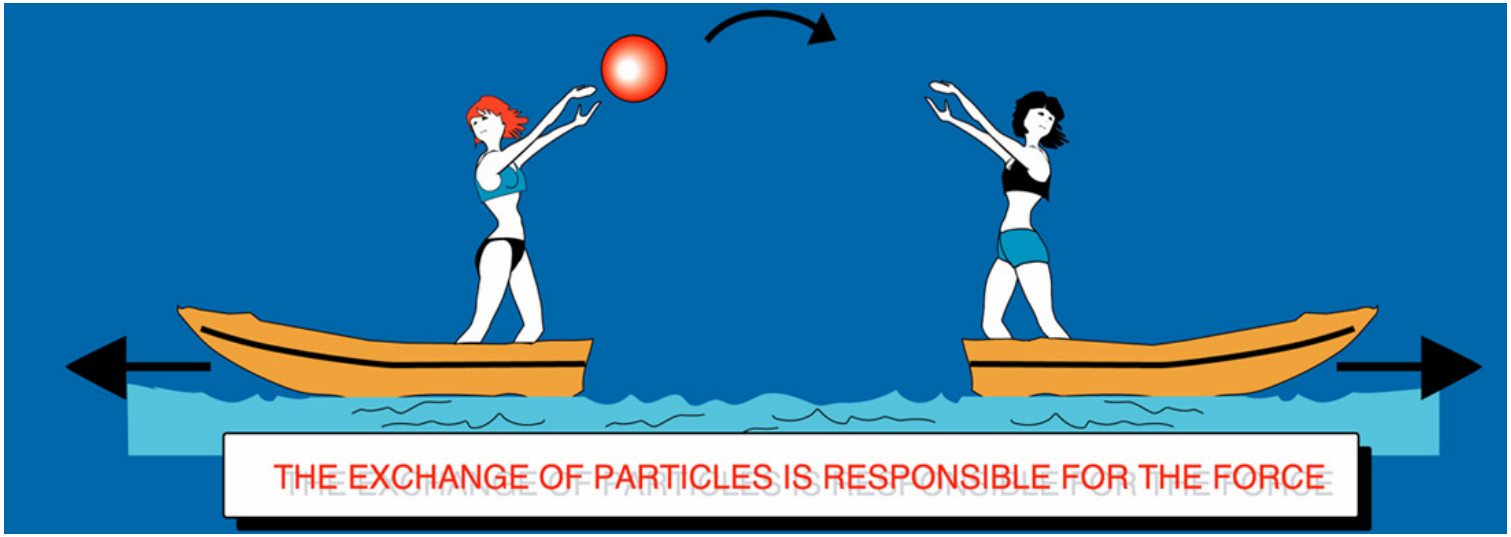


The Top Quark



What about the Forces?

The microscopic view of forces is that they are also caused by particles … being exchanged between the matter particles



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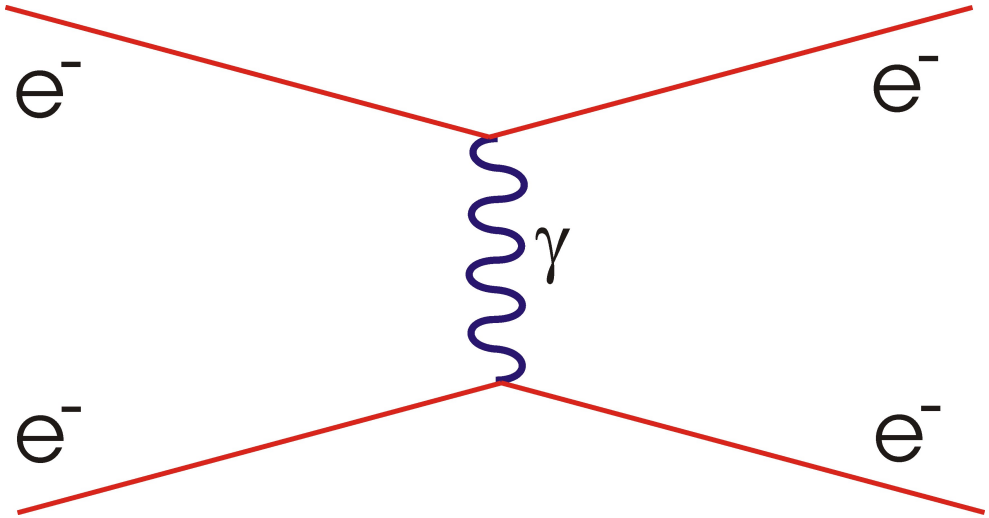
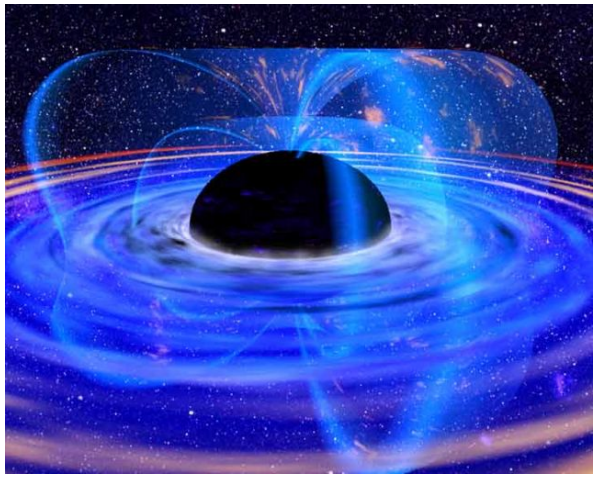


- e.g. if two negatively charged electrons come close, they repel one another … by exchanging a photon between them.
- The photon is the carrier of the electromagnetic force

The 4 Forces

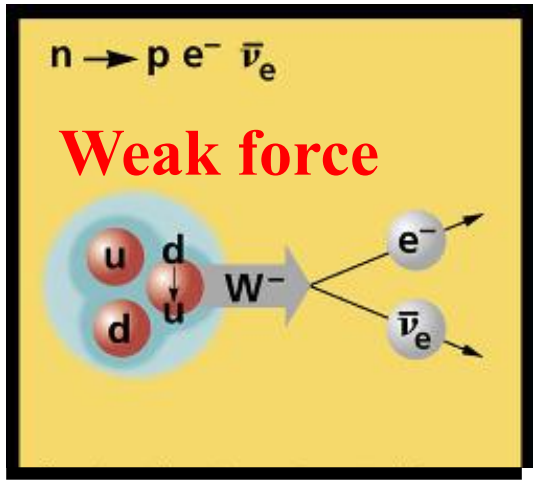


1) Gravity – stars, planets etc

2) Electromagnetic – atoms, electricity, everything in our everyday lives

3) Strong Nuclear Force – holds quarks together in protons and p, n in nuclei

4) Weak nuclear force – β decay … how stars generate energy



Force	Range	Mediator	Rel. Strength
Gravitational	long	graviton (massless)??	1
Electromagnetic	long	photon (massless)	10^{35}
Weak	short	W, Z bosons (heavy)	10^{33}
Strong	short	gluons (massless)	10^{38}

What about Antimatter?

Paul Dirac discovered the theory of the electron (1928), but for it to work, there had to be an anti-electron (or `positron')

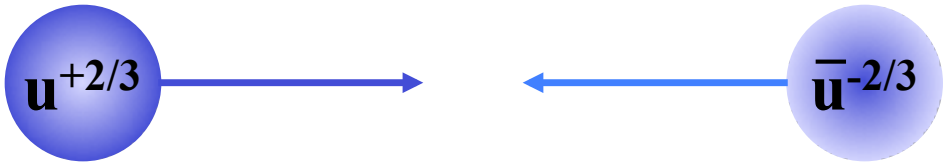
In fact, every fundamental particle has an antiparticle, with the same mass, but opposite charge.

electron e^- e^+ positron

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

etc etc ...

When matter and antimatter meet …



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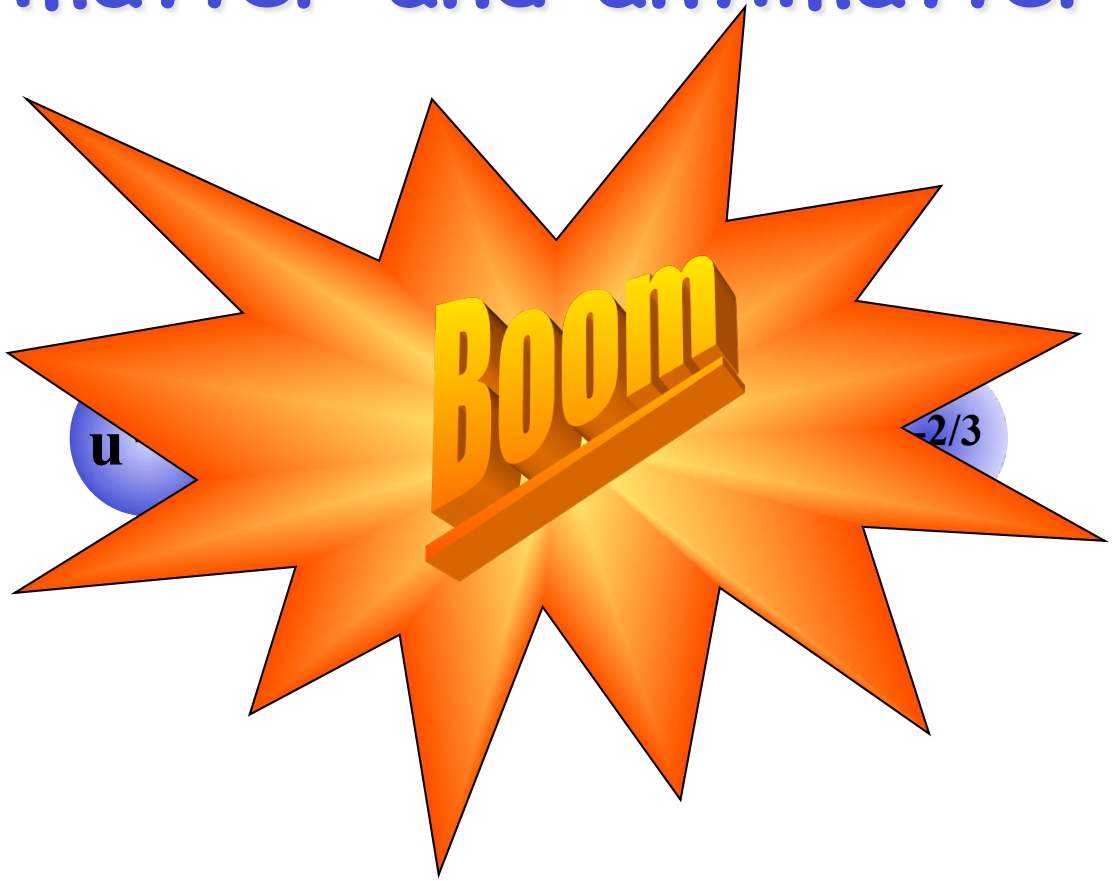
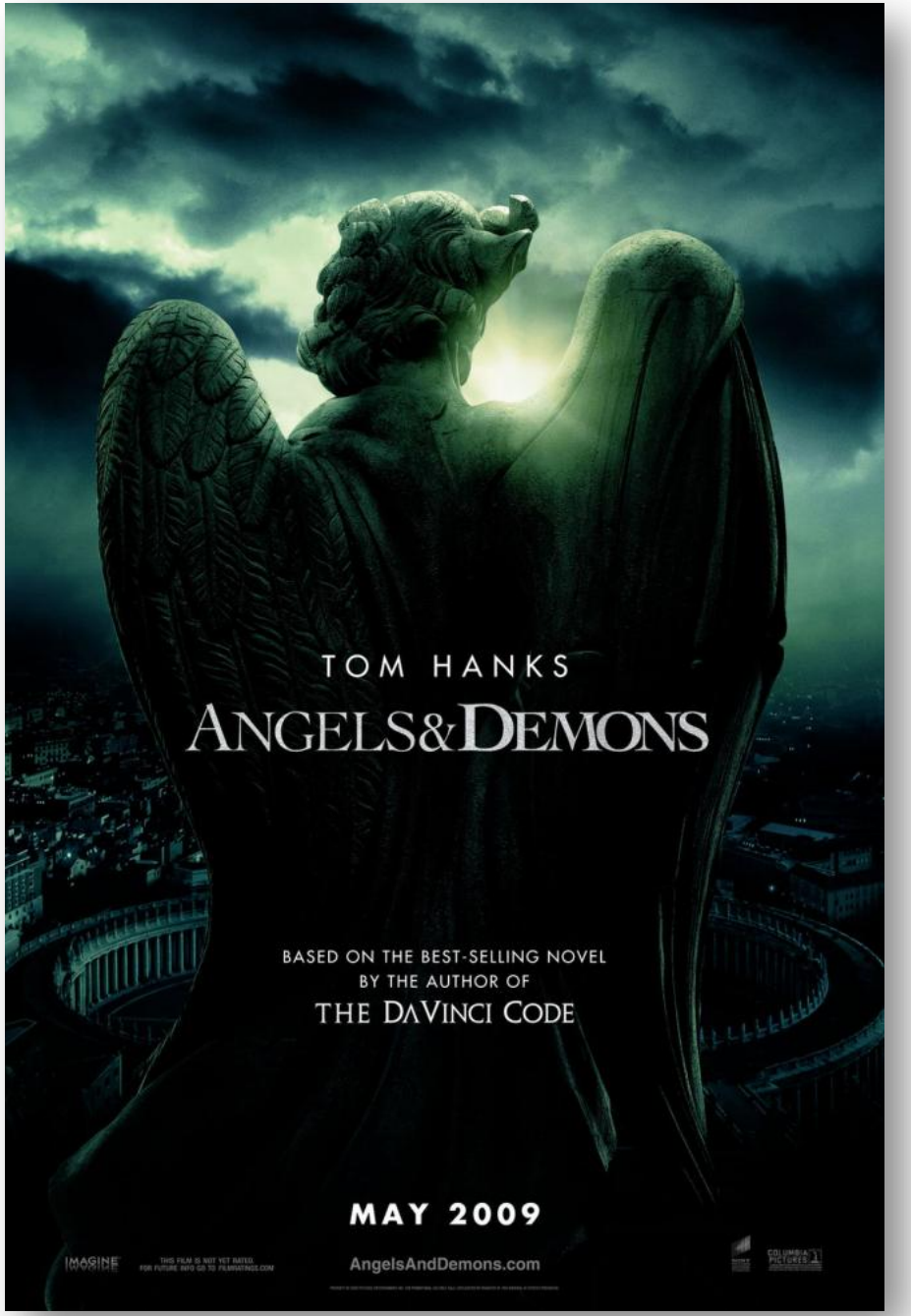


• If a particle and an antiparticle, each of mass m, collide, they annihilate, producing energy $E = 2mc^2$

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



In the Angels and Demons story, the bad guys go to CERN and steal half a gram of antimatter in a canister, which they take to Rome to use as a bomb.

Is the Antimatter at CERN Dangerous

If we had some means to accumulate half a gram and

if we could put it in a container and

if we could transport it to another site,

it would indeed be a powerful bomb!

Half a 5 pound note weighs about ½ gram!

If ATLAS could somehow accumulate all the antimatter it produced, it would take 10 million years to get ½ a gram of antimatter.

What will a Proton Look like at the LHC?

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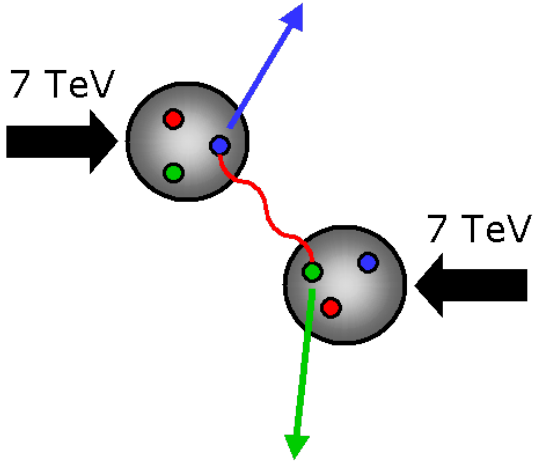
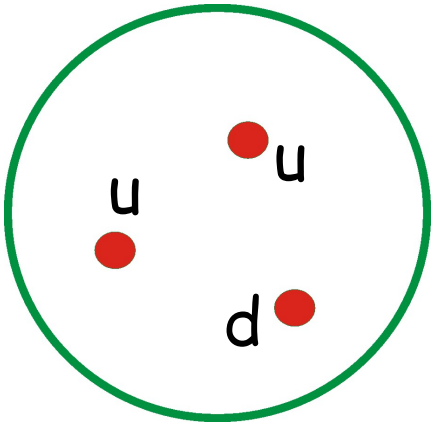
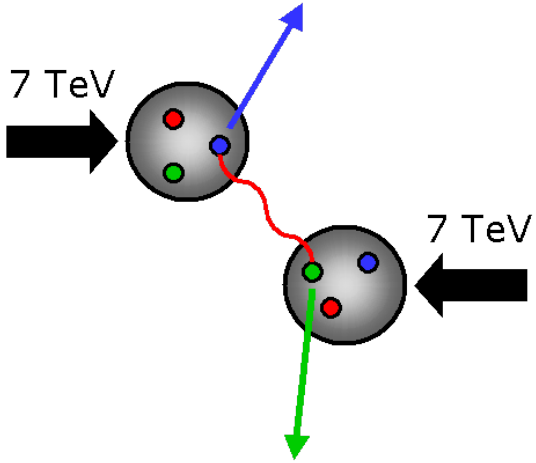


… when two protons collide hard at the LHC, it's the quarks and gluons inside them that will interact with one another, through the strong, electromagnetic and weak forces.

What will a Proton Look like at the LHC?





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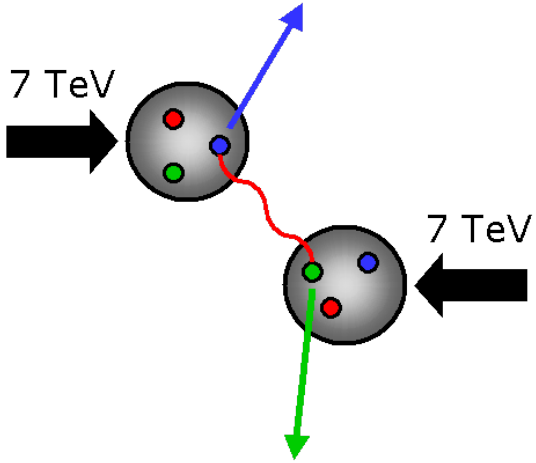

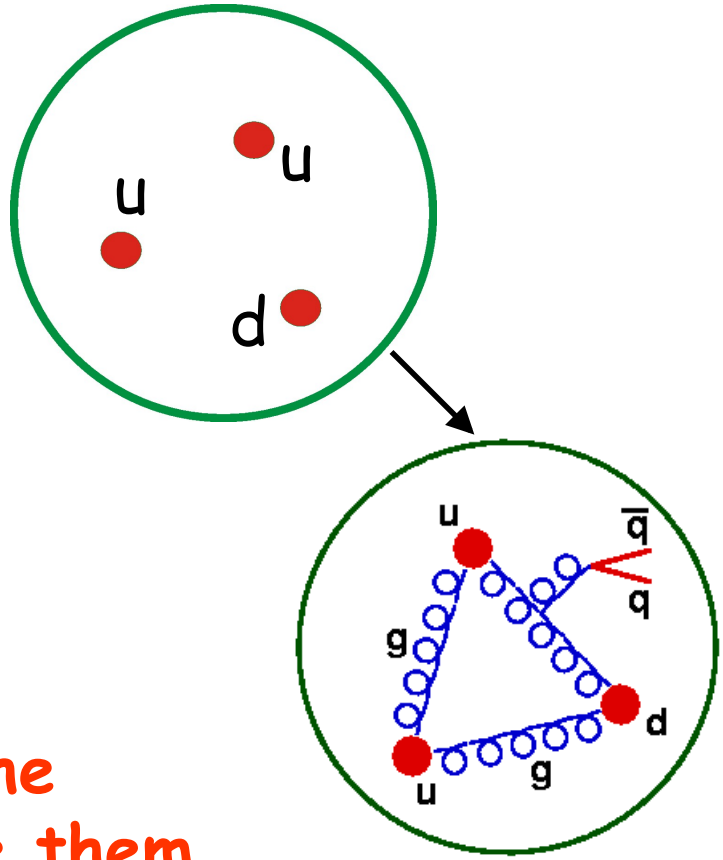

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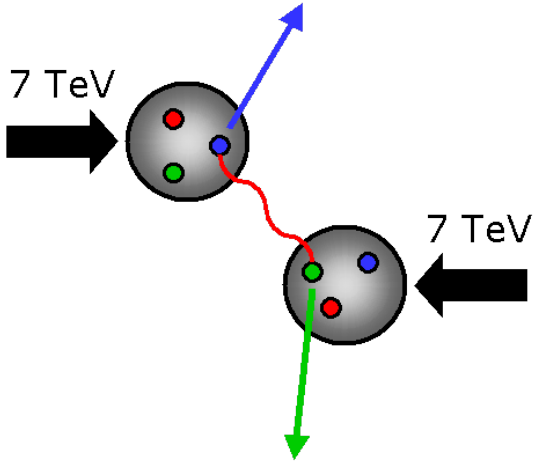
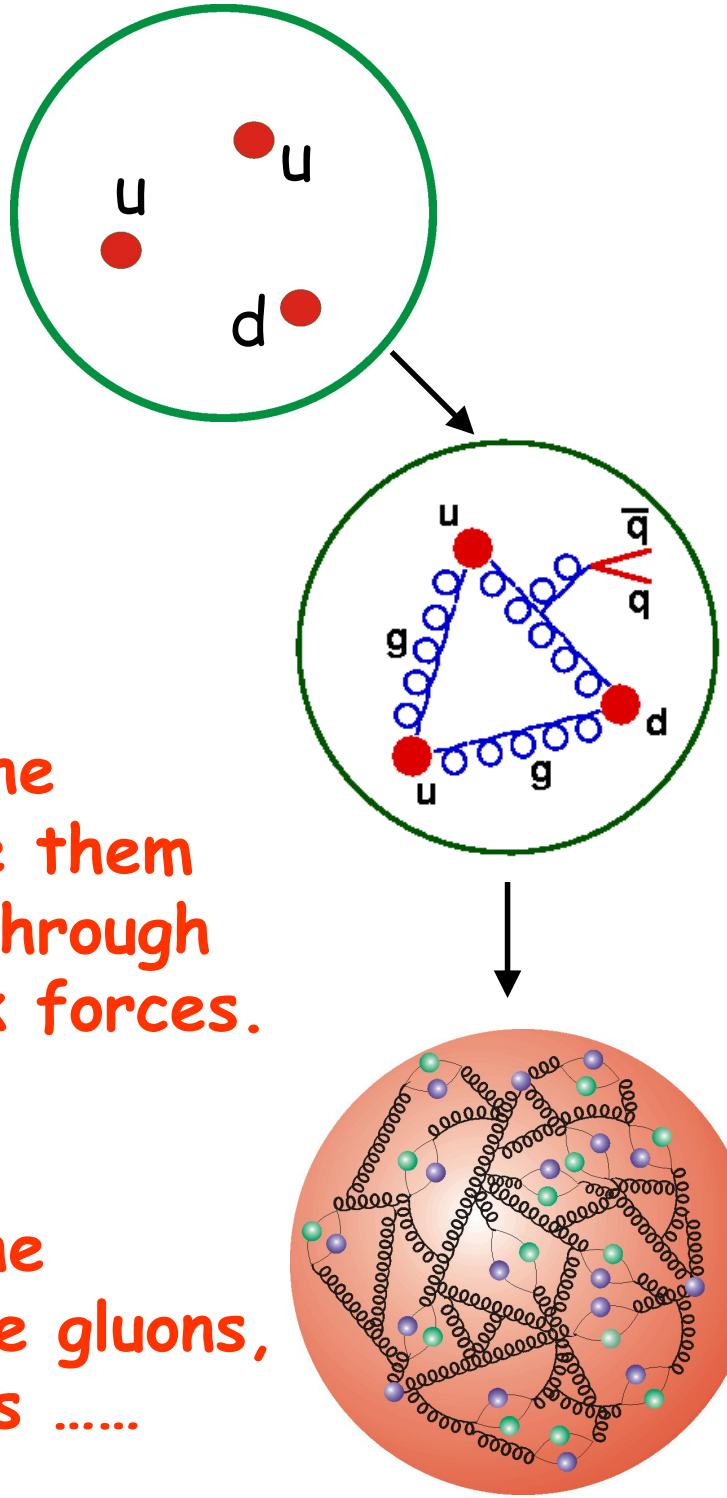




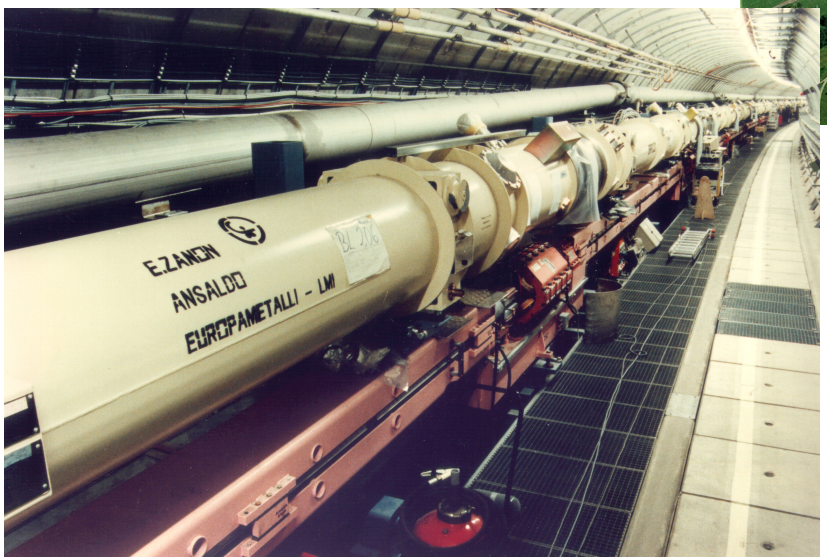
… when two protons collide hard at the LHC, it's the quarks and gluons inside them that will interact with one another, through the strong, electromagnetic and weak forces.

The modern view of the proton is complicated!… within the bounds of the uncertainty principle, quarks can make gluons, gluons can make quark-antiquark pairs ……

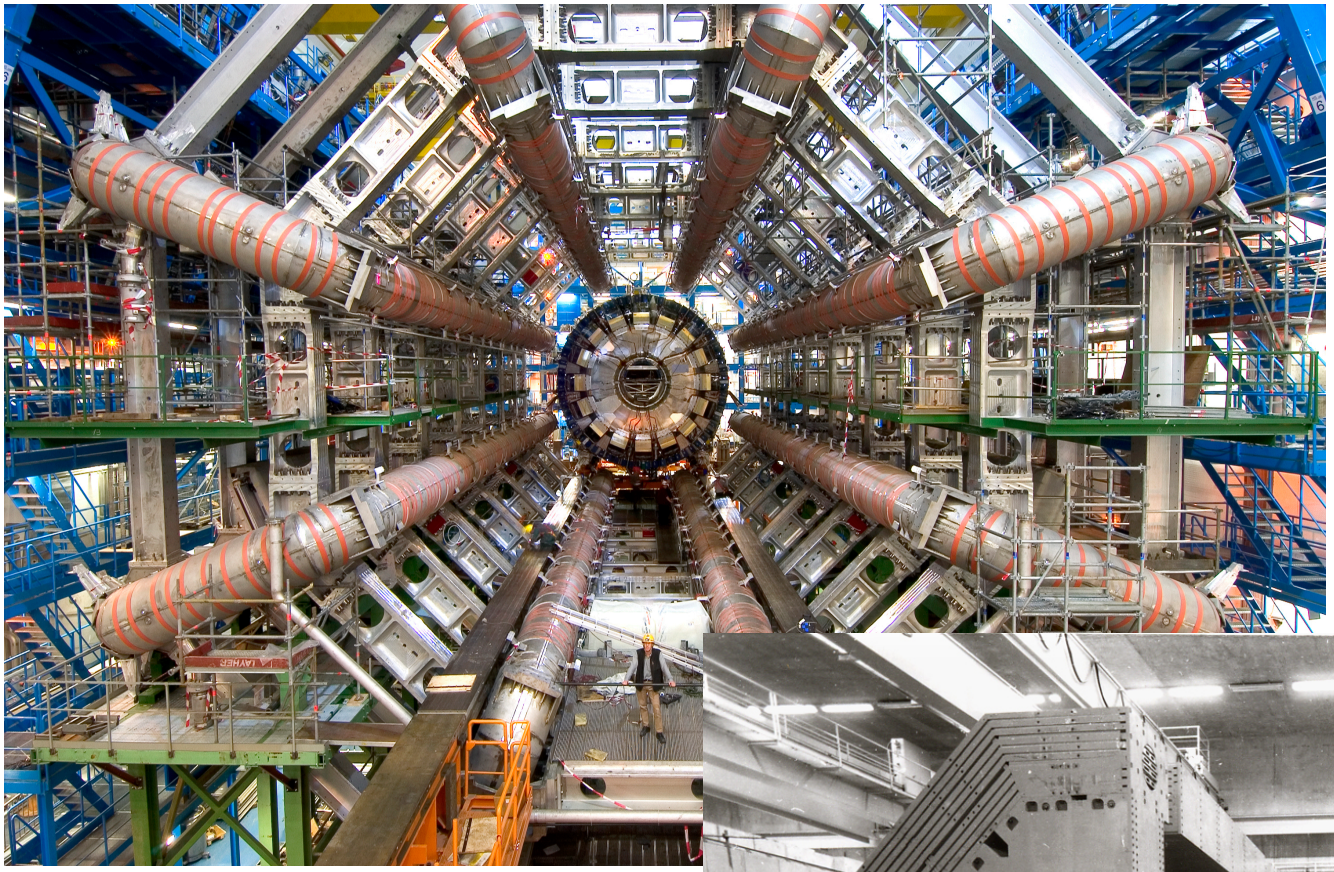
A Diversion to Hamburg

HERA (1992-2007)

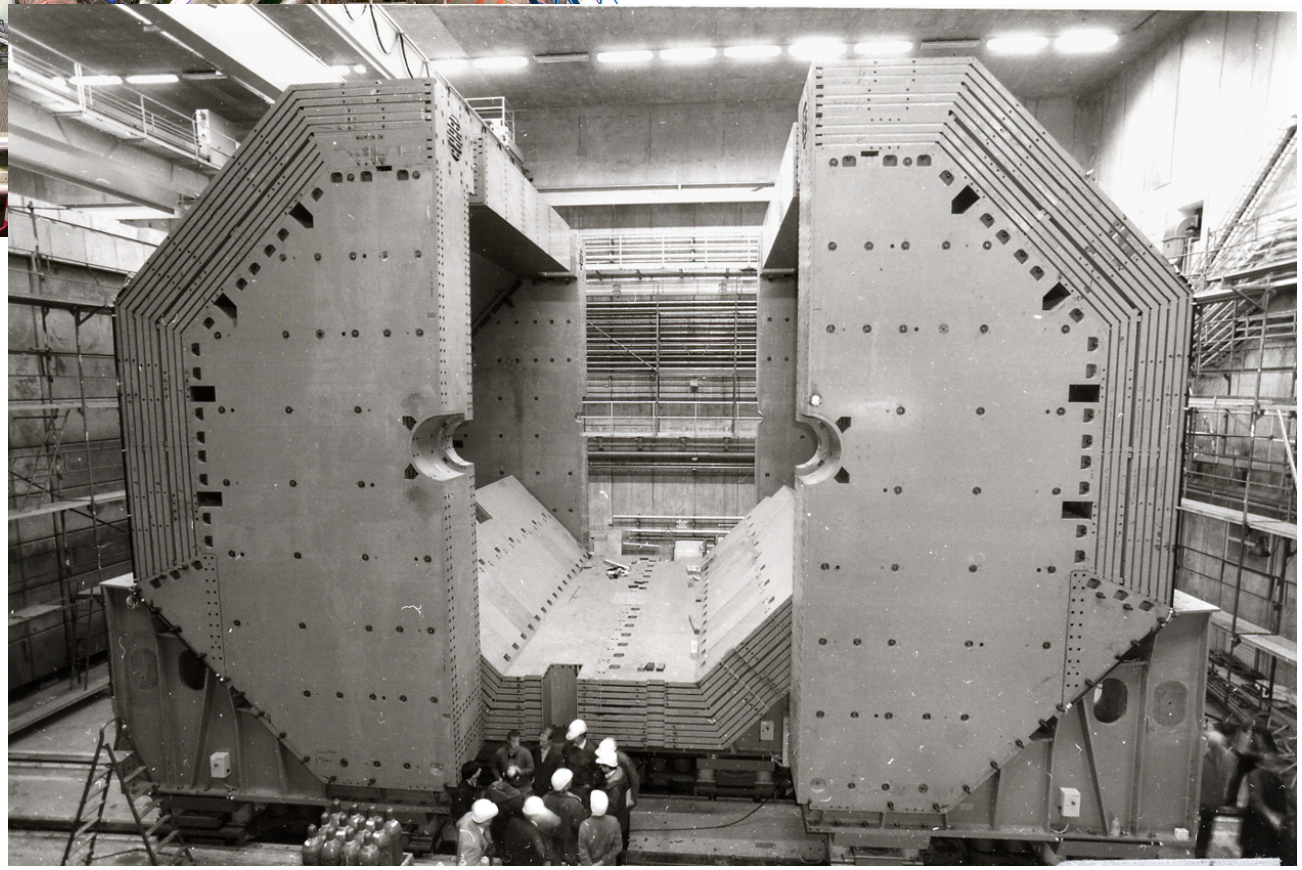
… the world's only ever electron-proton Collider



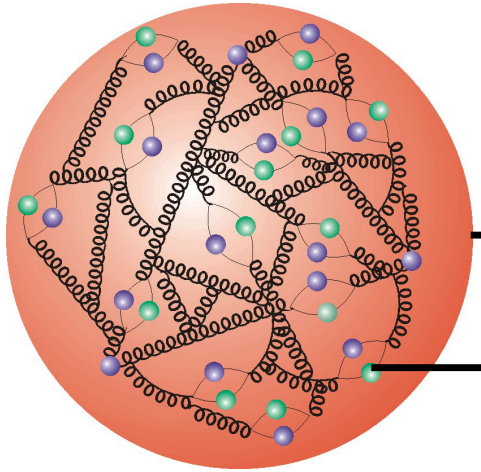
"The World's most powerful microscope" … looking inside the proton at distance scales of 10^{-18}m to see how it will look at the extreme energies of the LHC



Scale: H1 v ATLAS



Strong Birmingham involvement in the H1 experiment.



How is the Proton's Momentum Shared out?

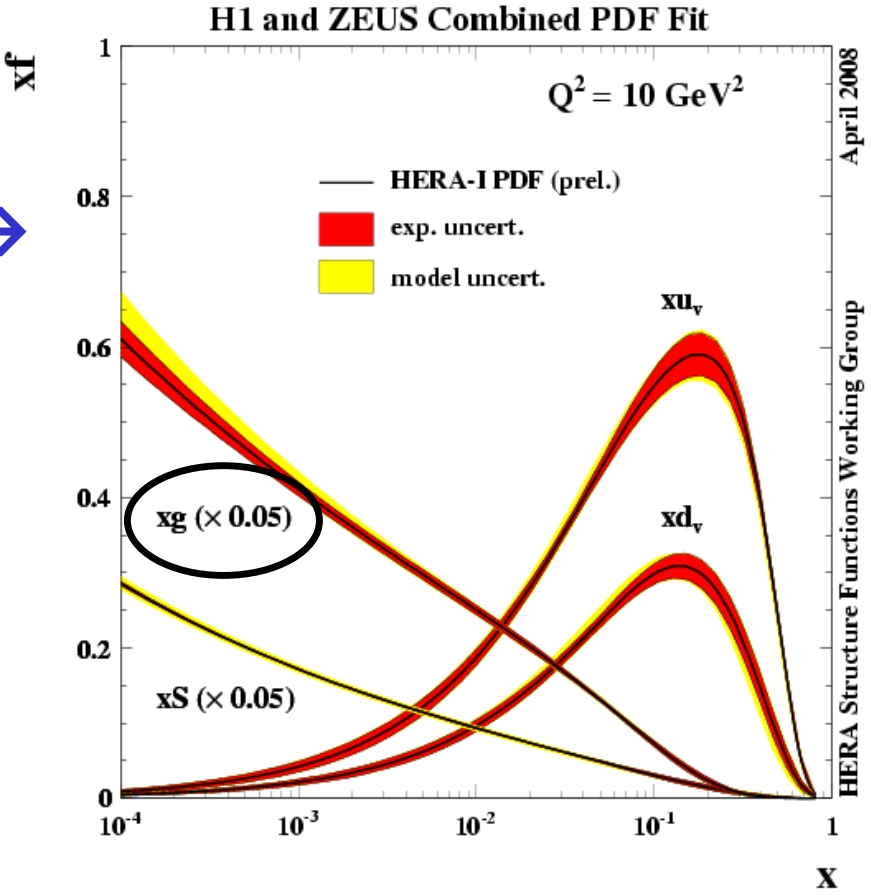
Each LHC proton has momentum 7 TeV / c

A quark with momentum fraction of x has momentum (7x) TeV / c

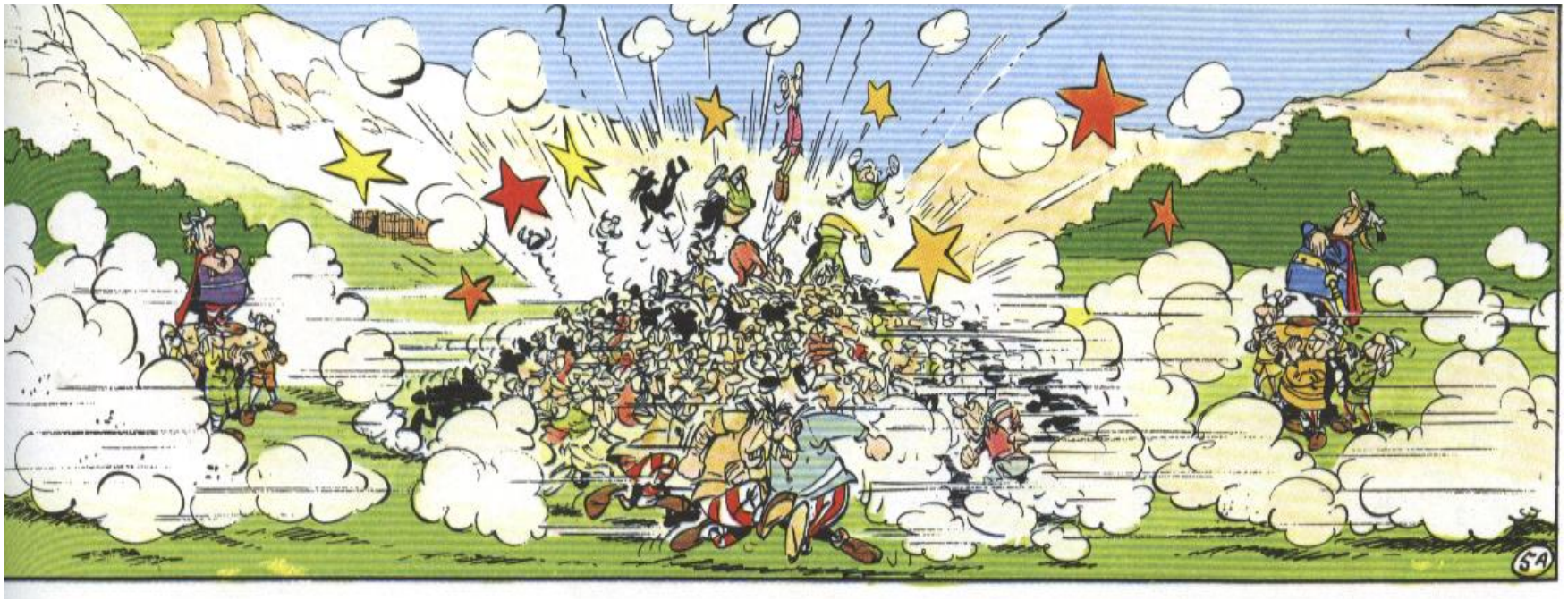
Momentum carried by quarks and gluons as a function of x →

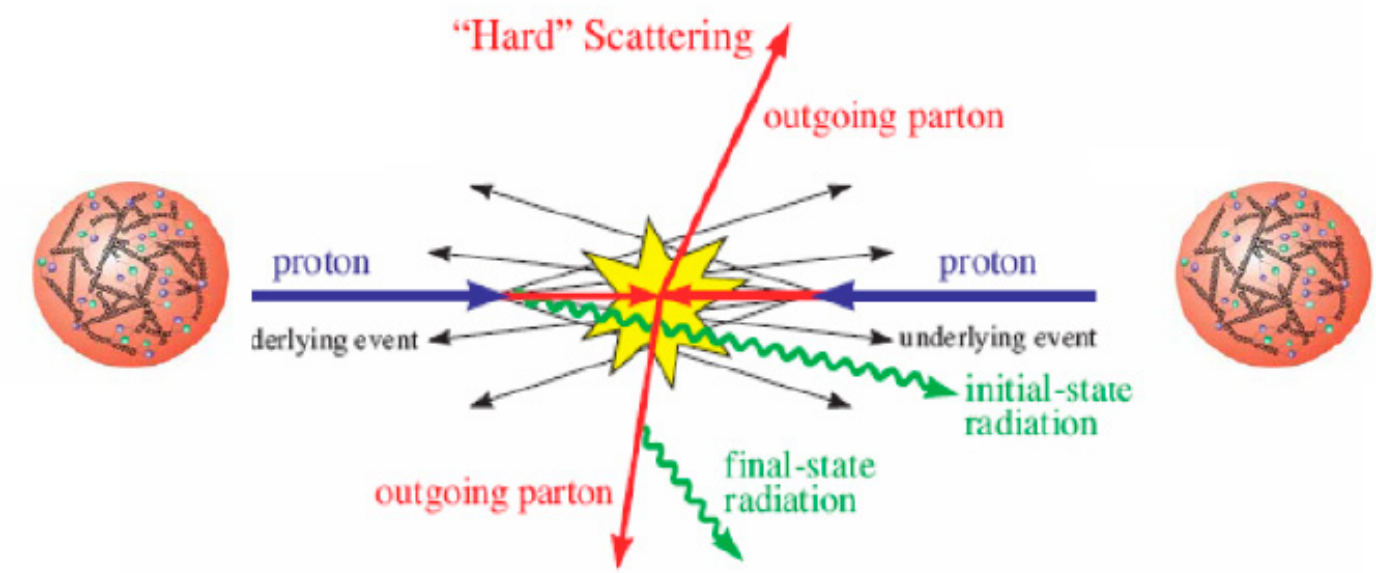
At LHC energies, a proton looks like a very complicated `bag' of quarks and gluons

In fact there are considerably more gluons than quarks!



Proton-proton collisions are, err, complex





Picking out the most interesting collisions and particles is a huge task

"Seeing" Particles at the LHC

We can't see the quarks produced in LHC collisions directly
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and decays fast to 2 photons ..... $\pi^0 \rightarrow \gamma\gamma$

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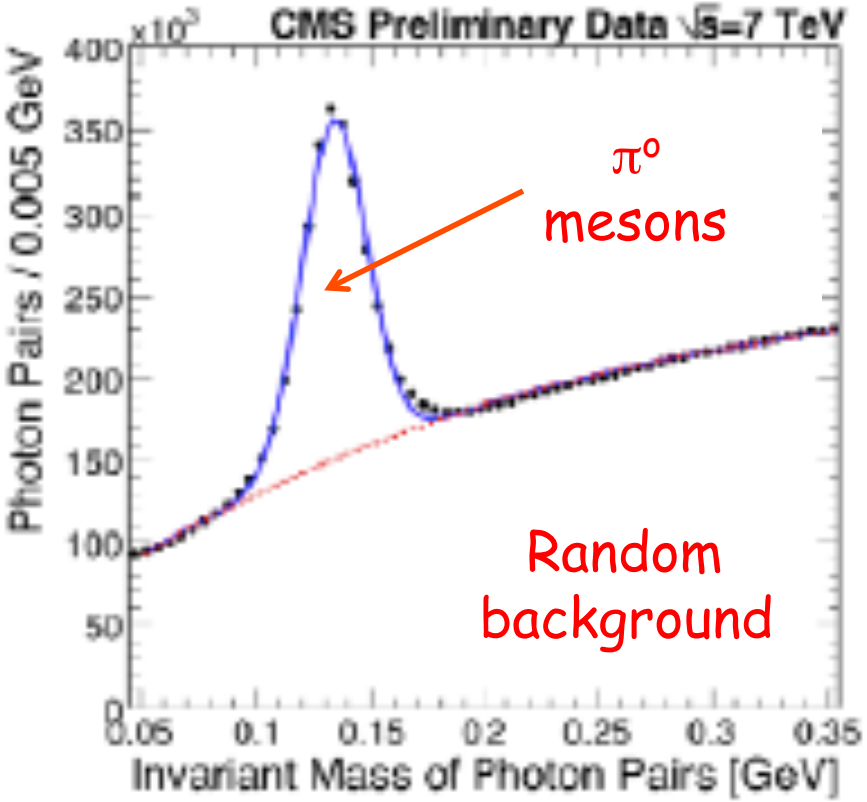

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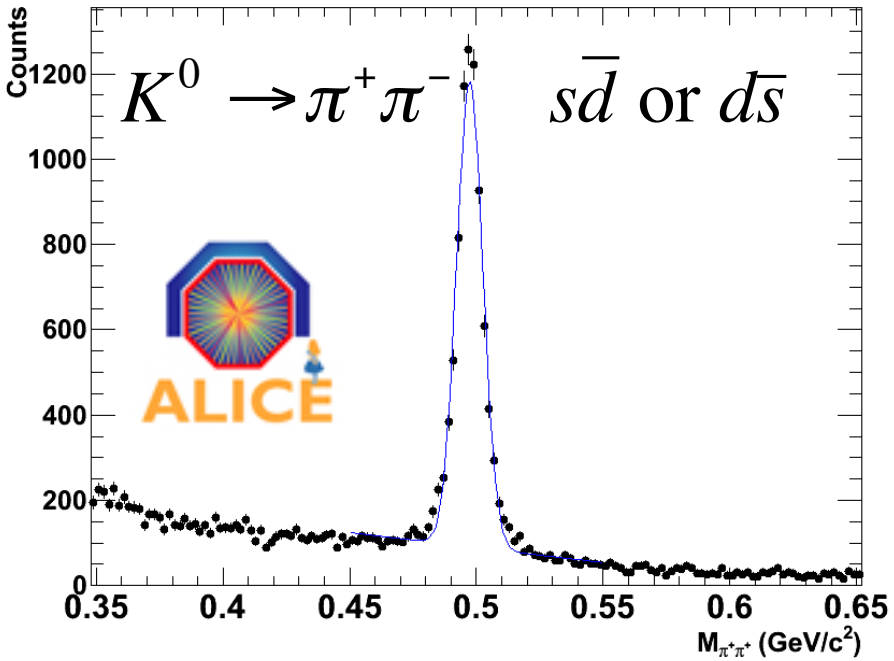
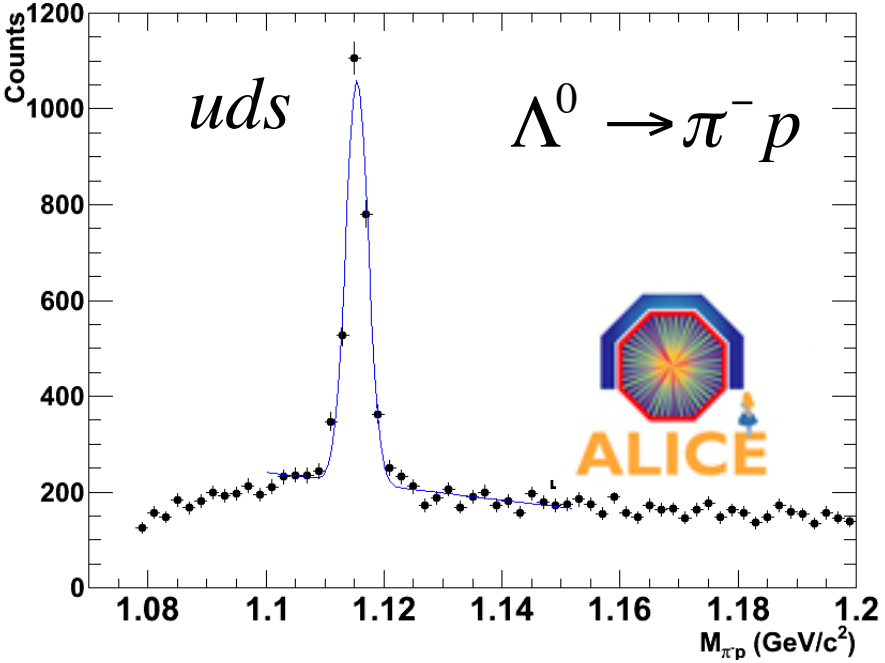
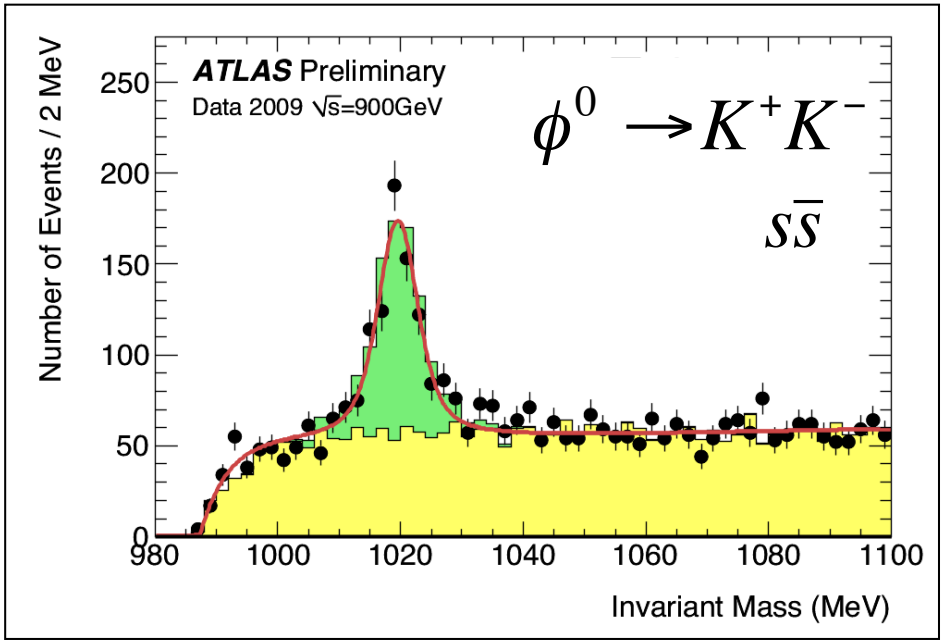
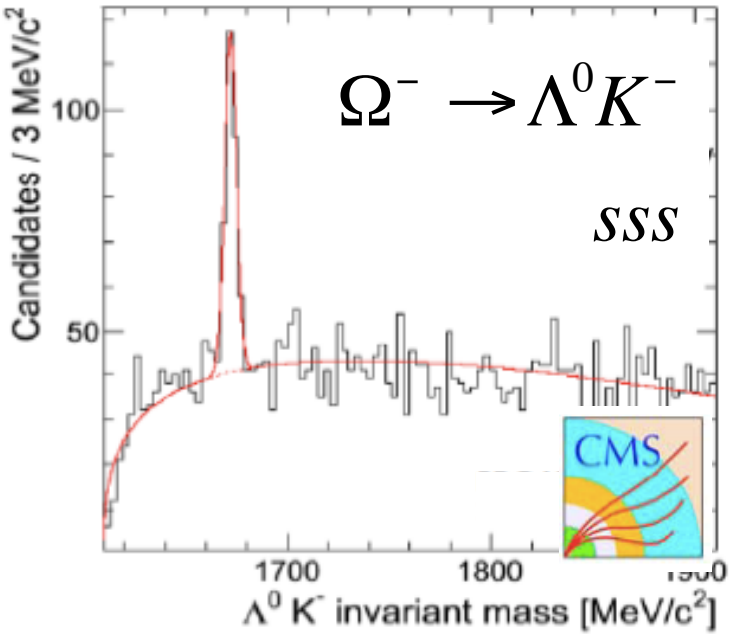
One of the first LHC plots!…

Early Strange Particle Sightings

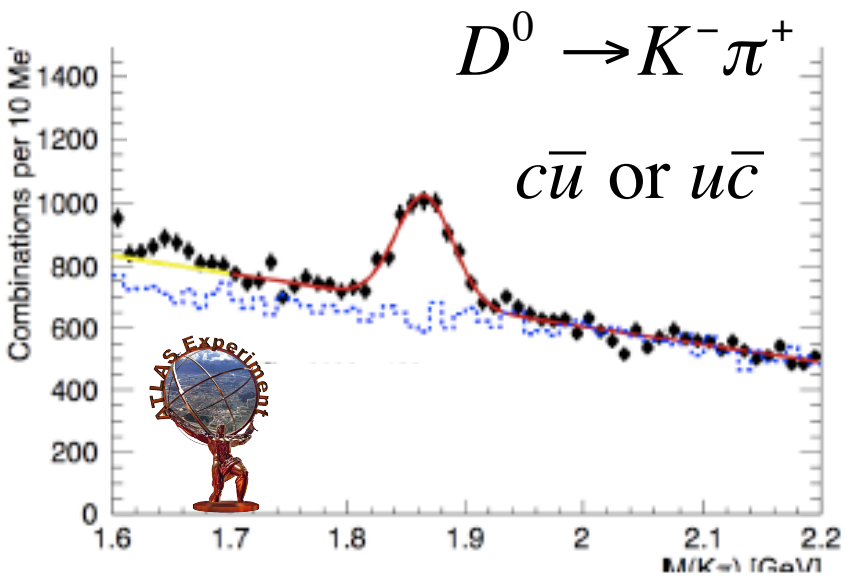


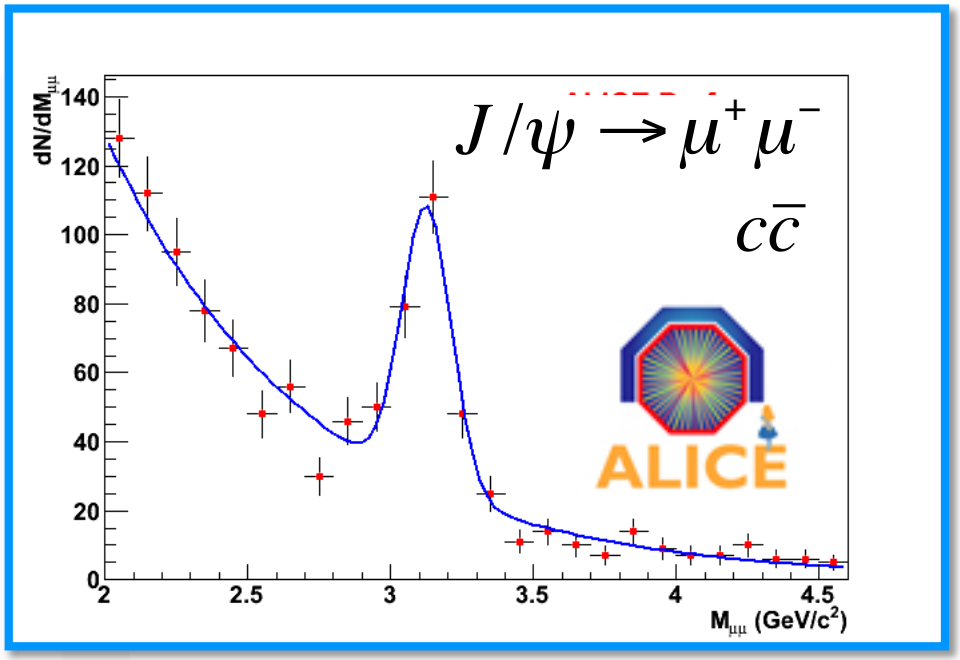


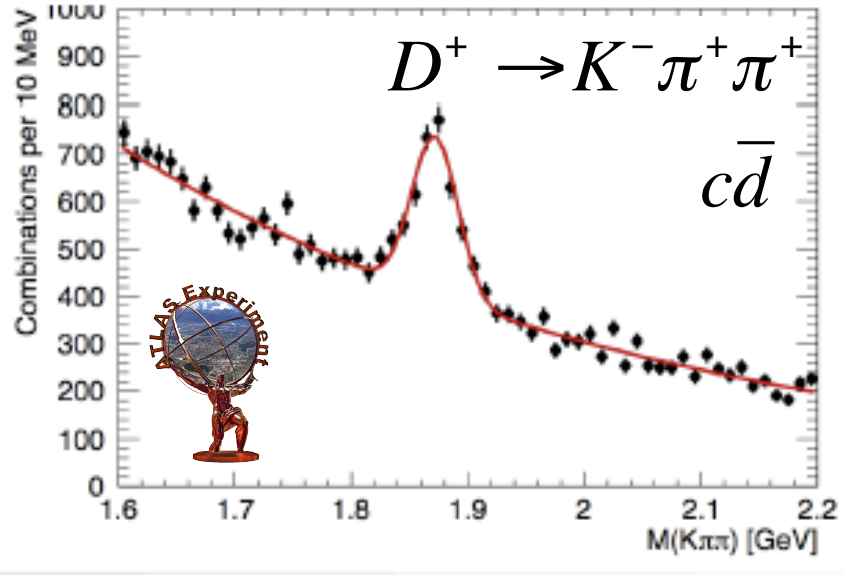


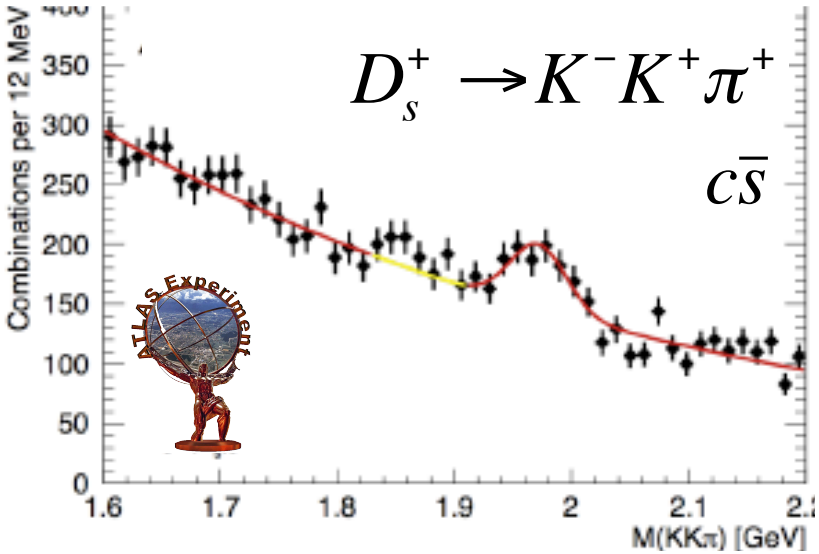


Early Charm Particle Sightings





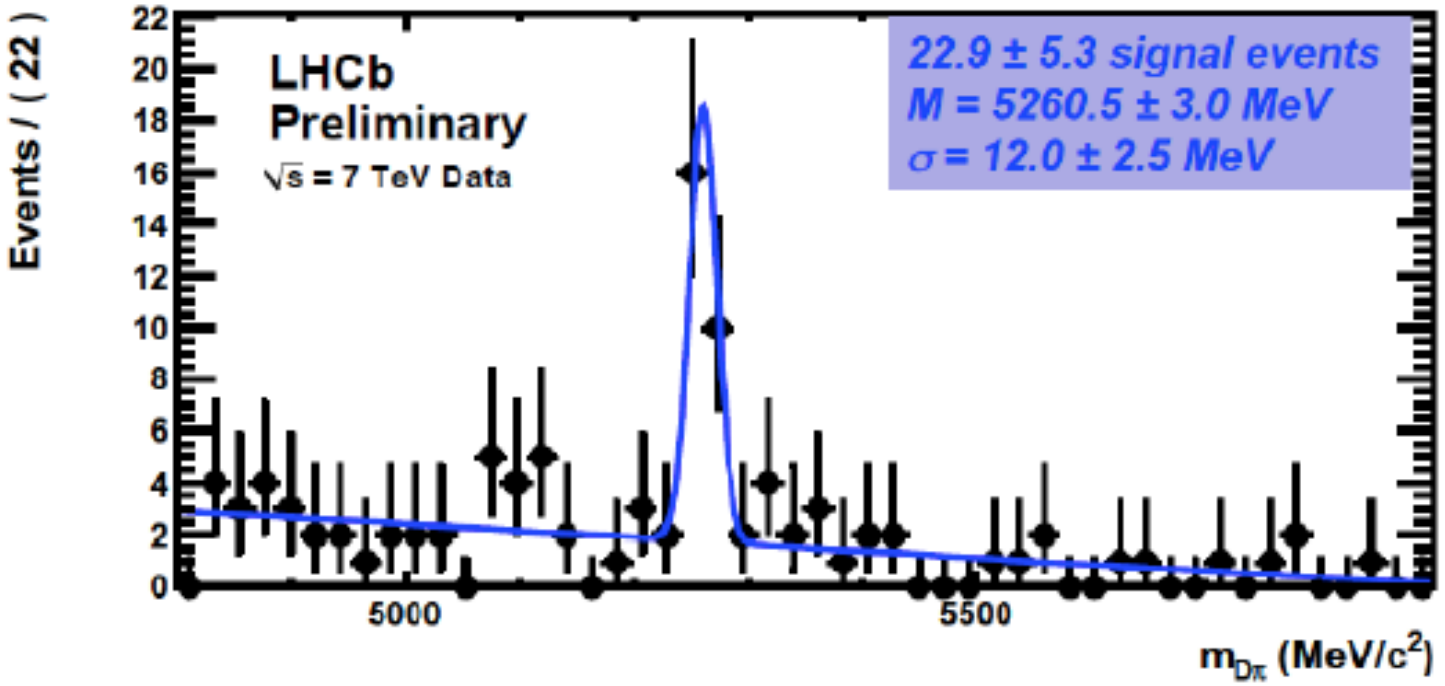




Early Beauty Particle Sightings

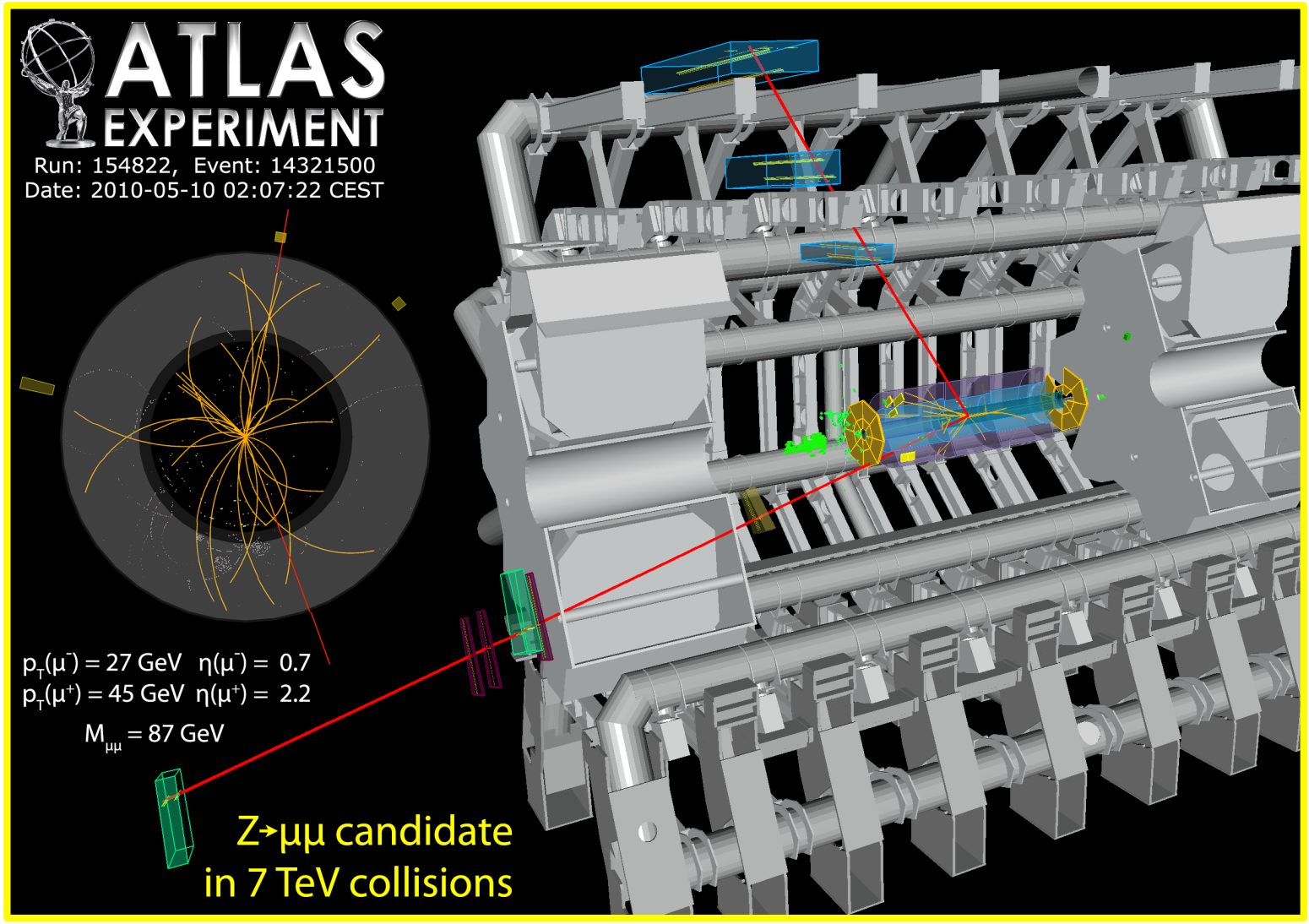
$$B^0 \to D^-\pi^+ \quad \text{and} \quad B^+ \to D^0\pi^+$$

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



No top quarks observed yet, but we're working on it!

Seeing the Weak Force Carriers



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

So what next?…

- The LHC accelerator is working well and the experiments are seeing the sorts of things they expect

… but it's early days and the beam intensities are still low

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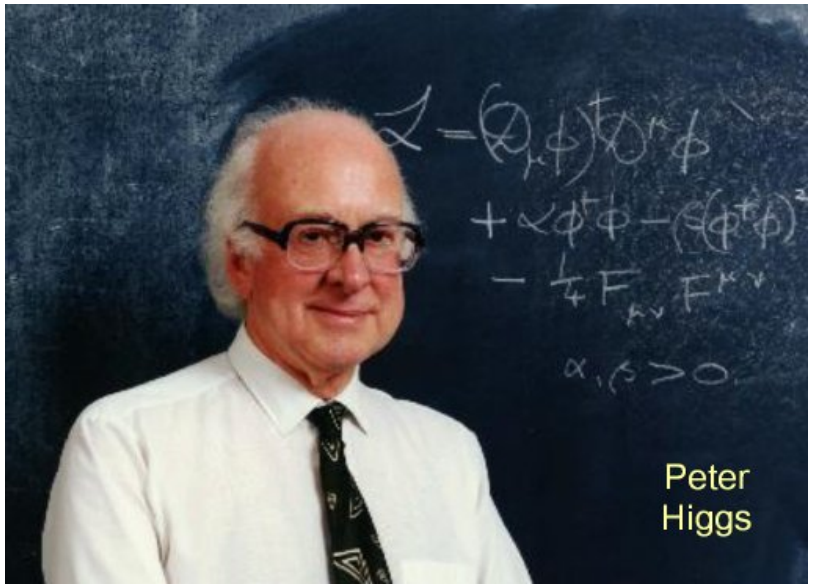
What might the LHC Discover?…

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

He proposed a new heavy particle, the Higgs Boson, which `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 ☹

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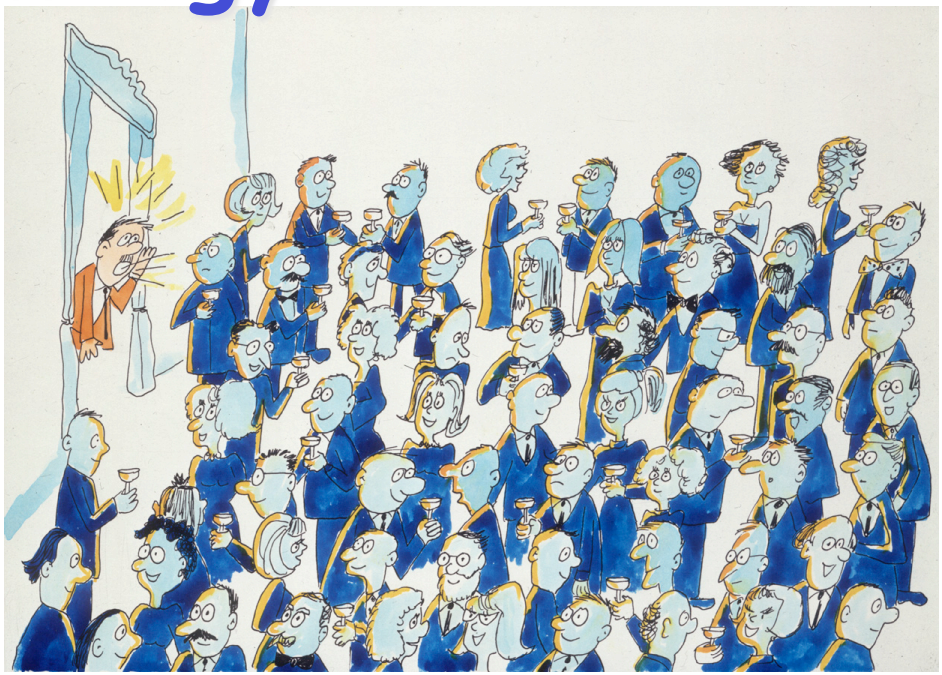

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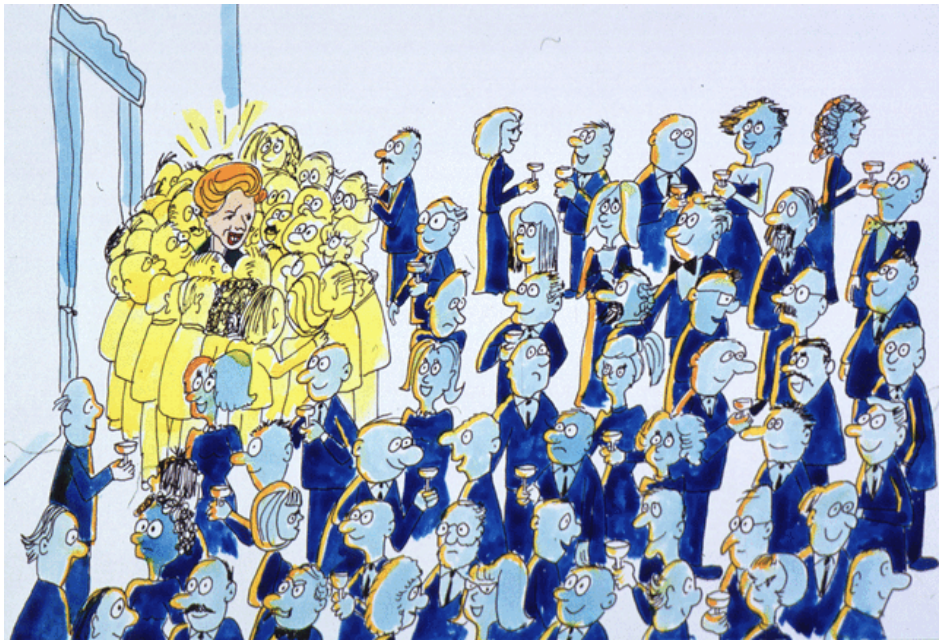


How a Higgs boson event might look in ATLAS

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

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

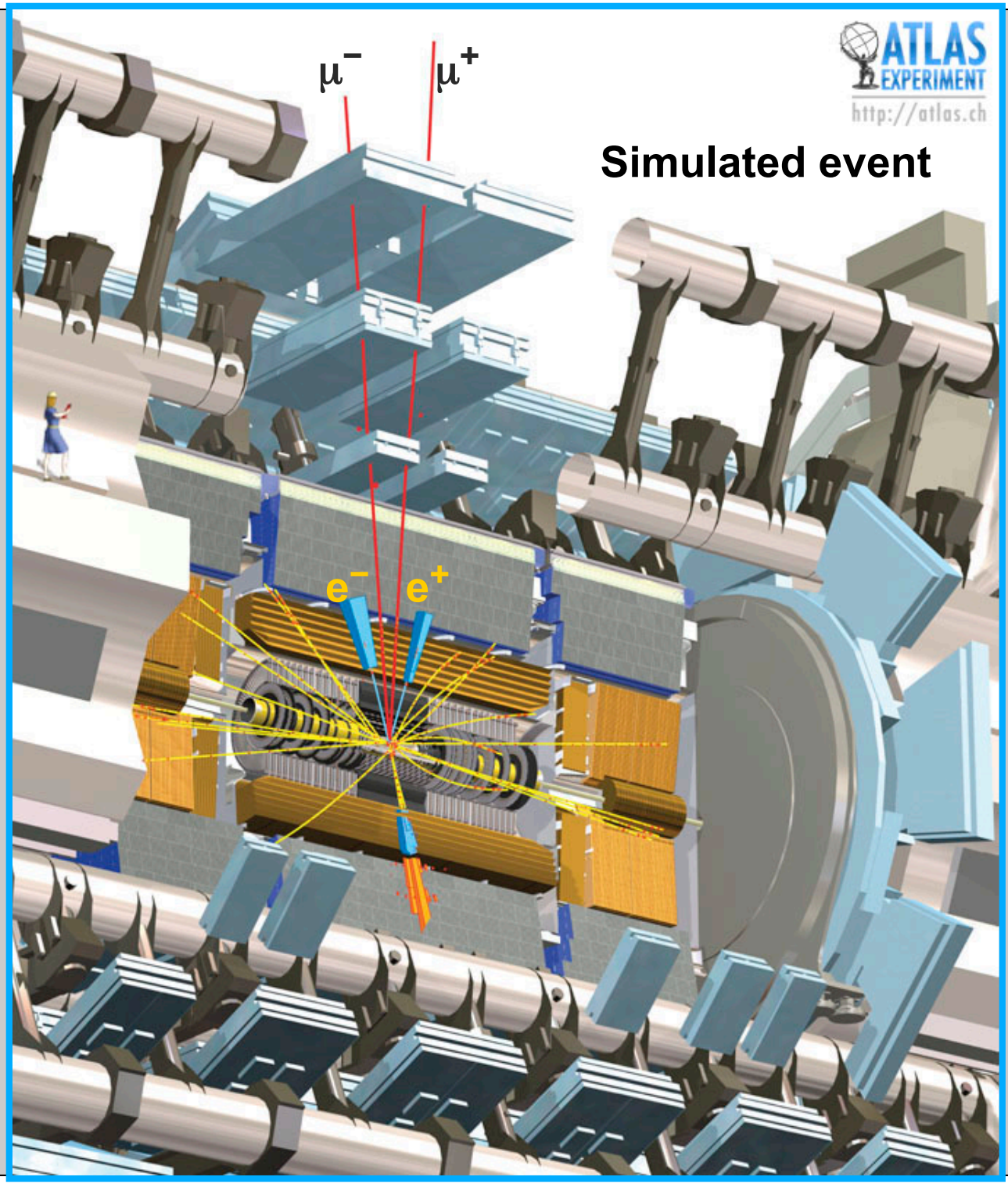
$H \rightarrow Z + Z$

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

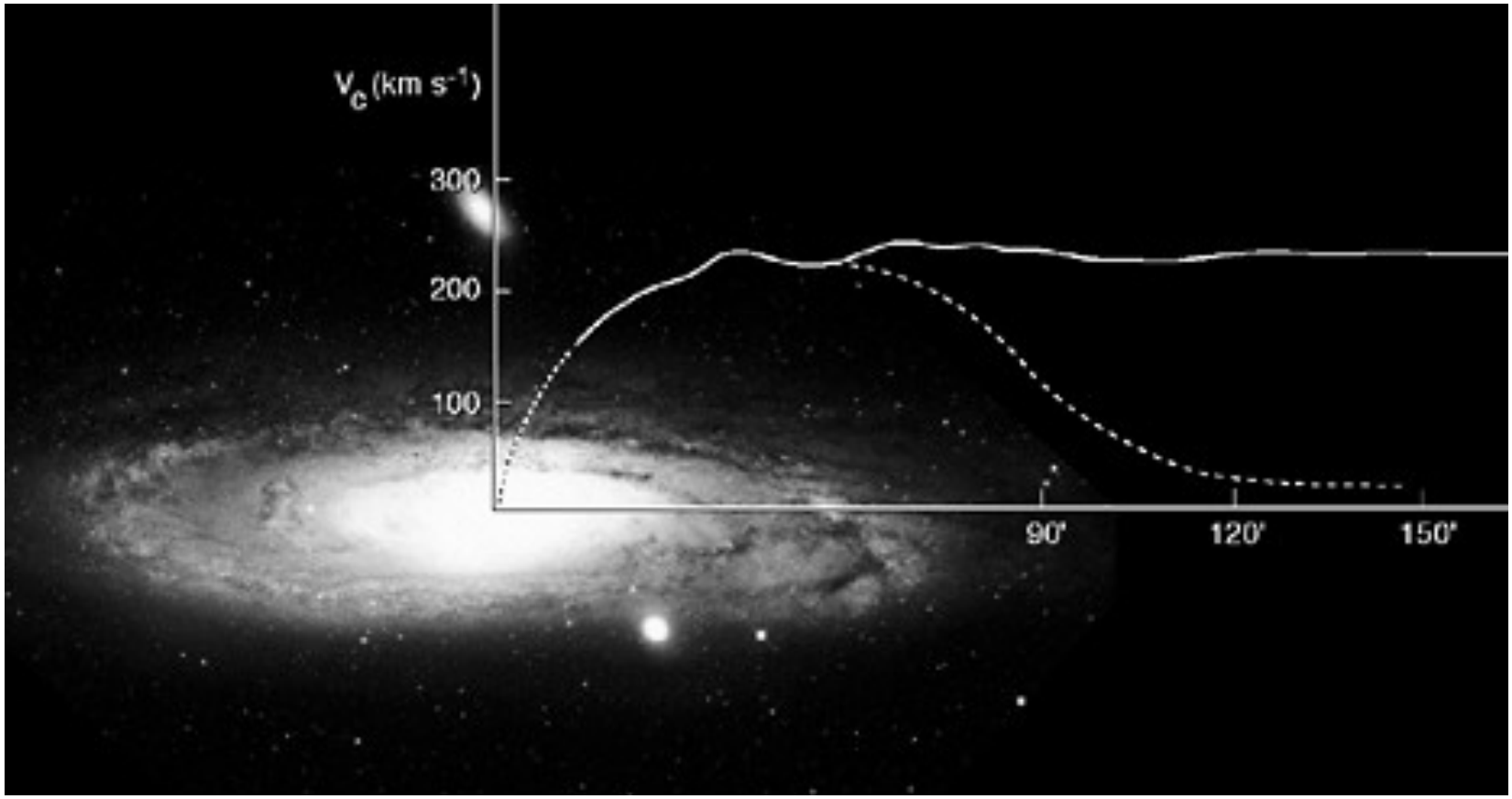
$Z \rightarrow \mu^- + \mu^+$

1 billion events per second

1 Higgs produced every 10 seconds!



A connection to the Universe

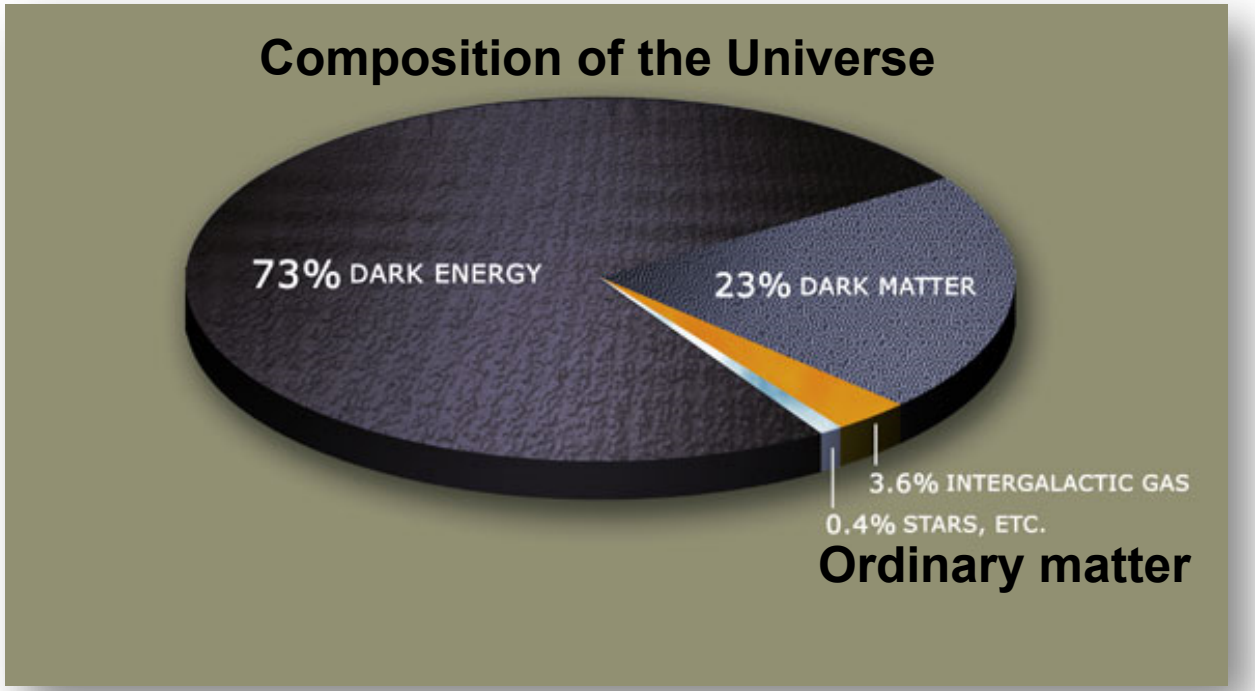


Looking at the relative rotation and gravitational attraction deep in the universe, either …

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)



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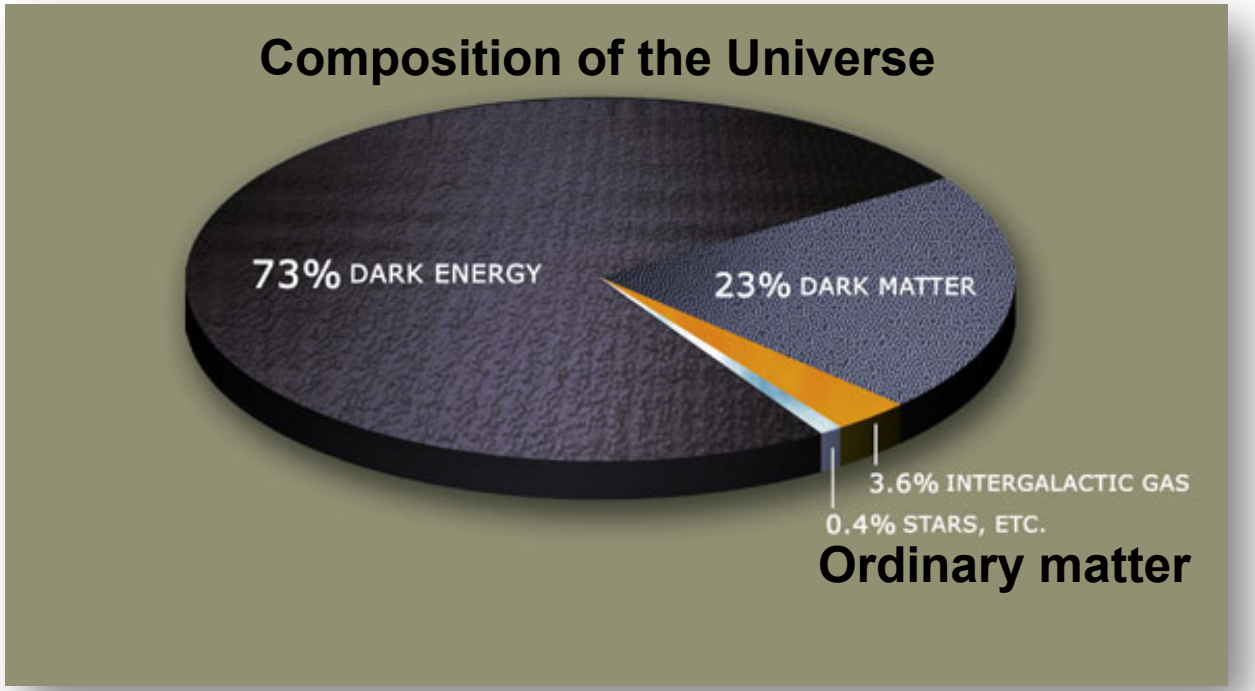

The dark side of the universe…

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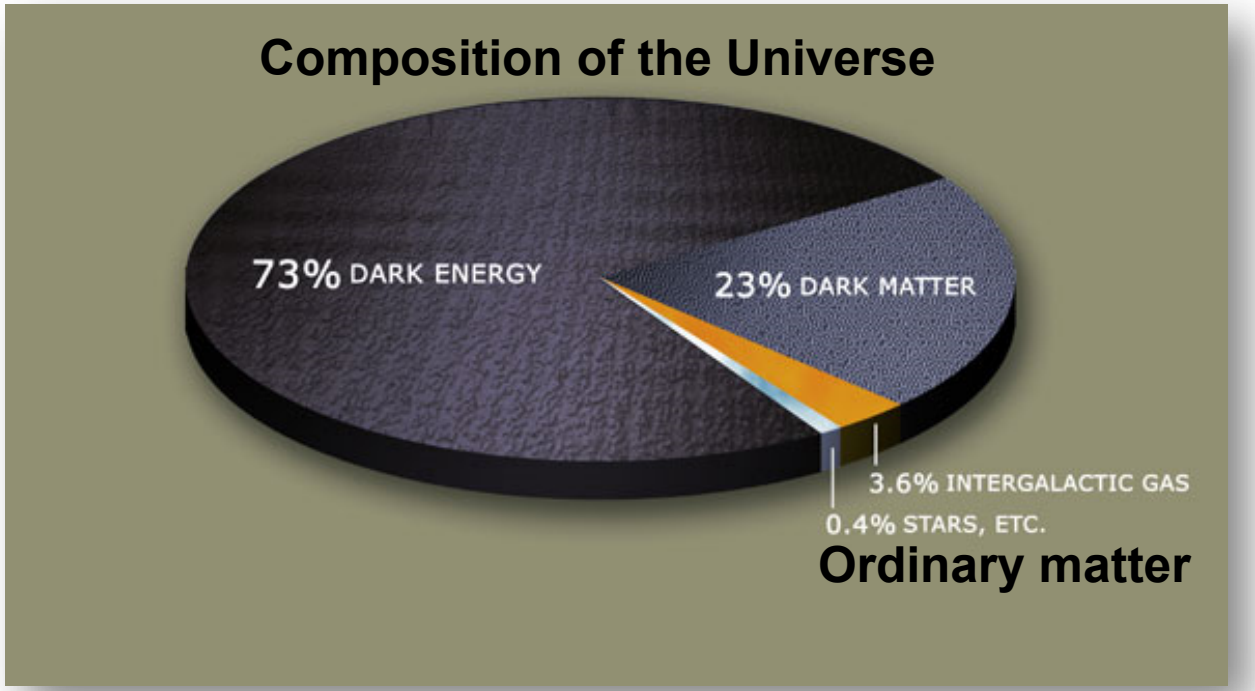


The dark side of the universe…

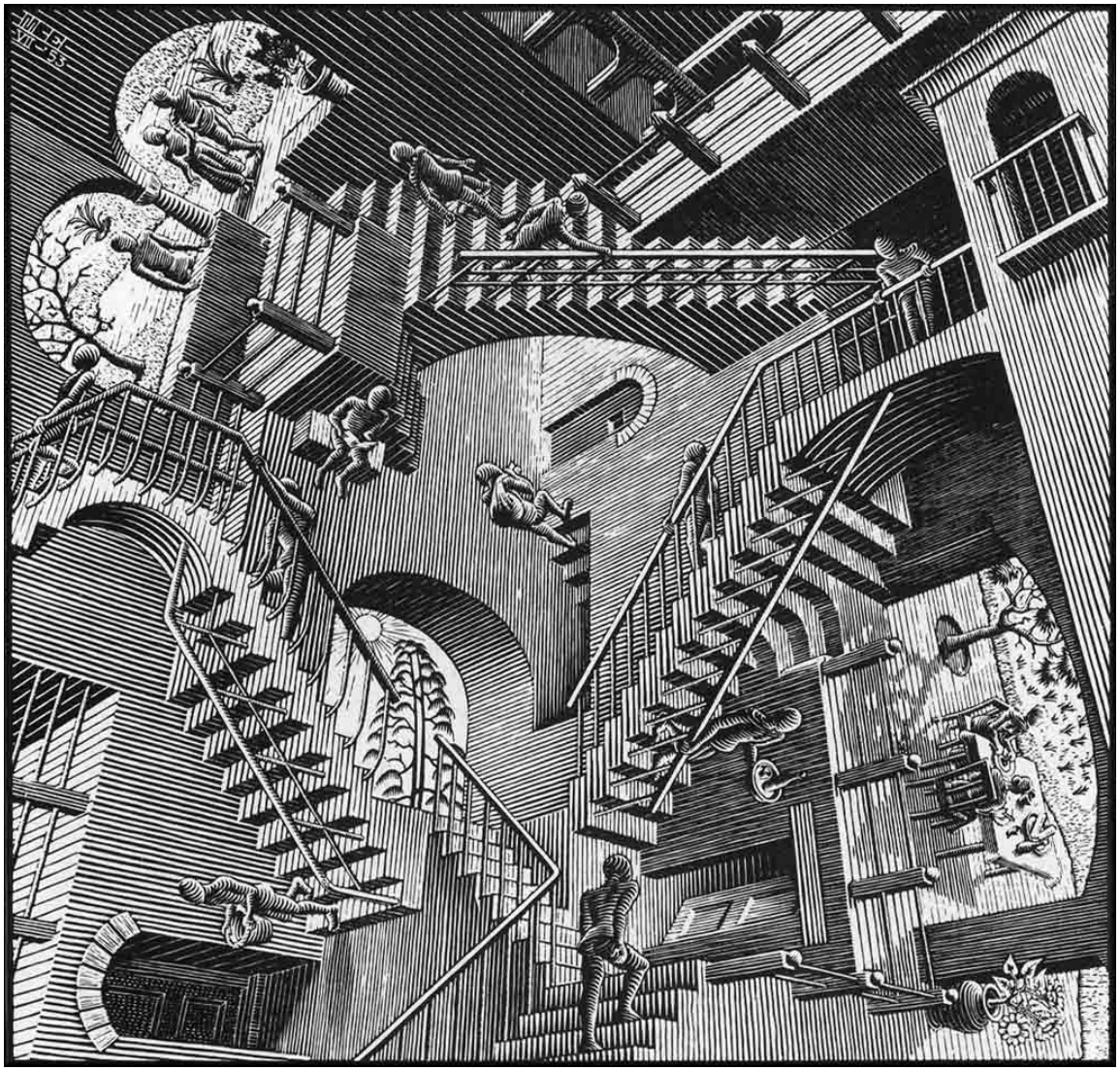
If dark matter is made up of unknown elementary particles, they could be discovered at the LHC. e.g. Supersymmetry …

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

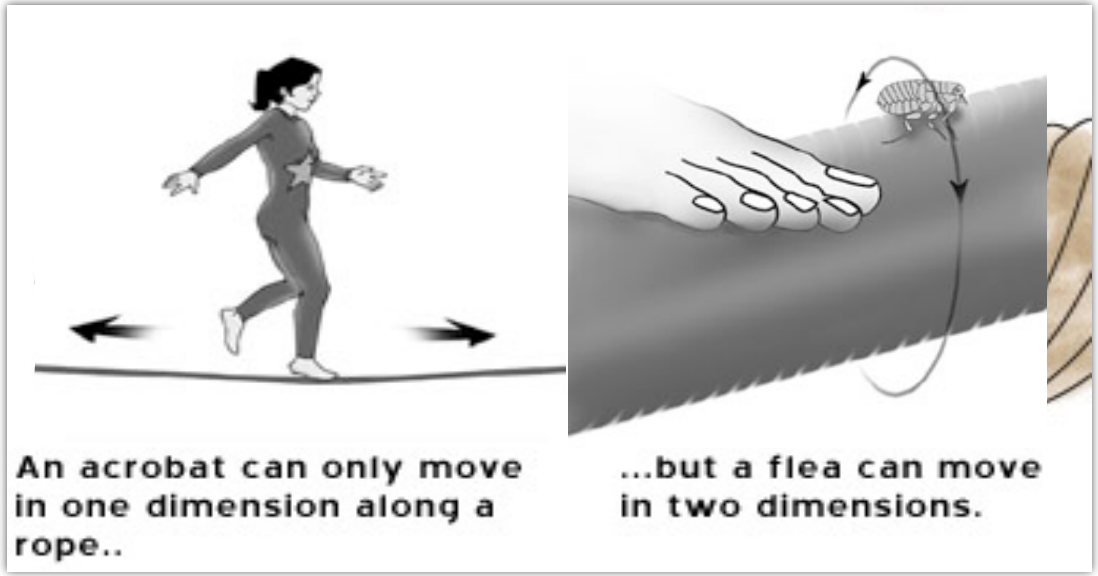


- it's OK …they're quite safe ☺

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.

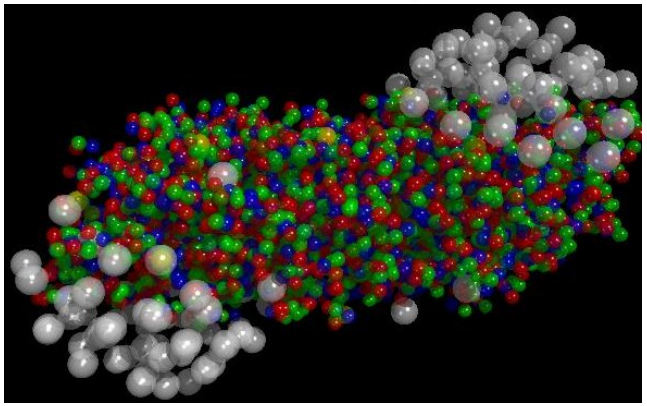


Maybe there could be inperceptible extra dimensions curled up like this by gravity?

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

ALICE and the Quark Gluon Plasma

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



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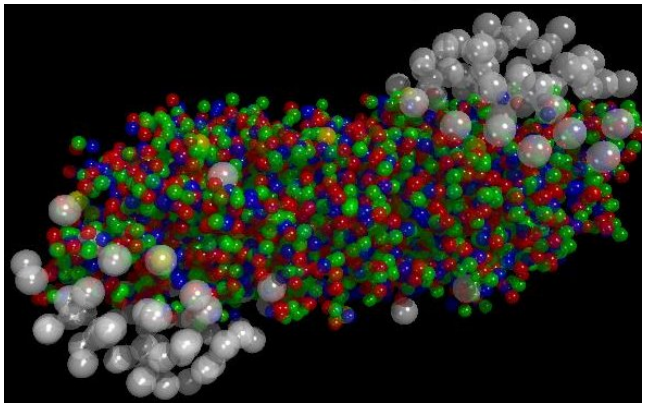

… this should recreate a state of matter in which hadrons 'dissolve' to produce a soup of unbound quarks and gluons (a 'Quark-Gluon Plasma')

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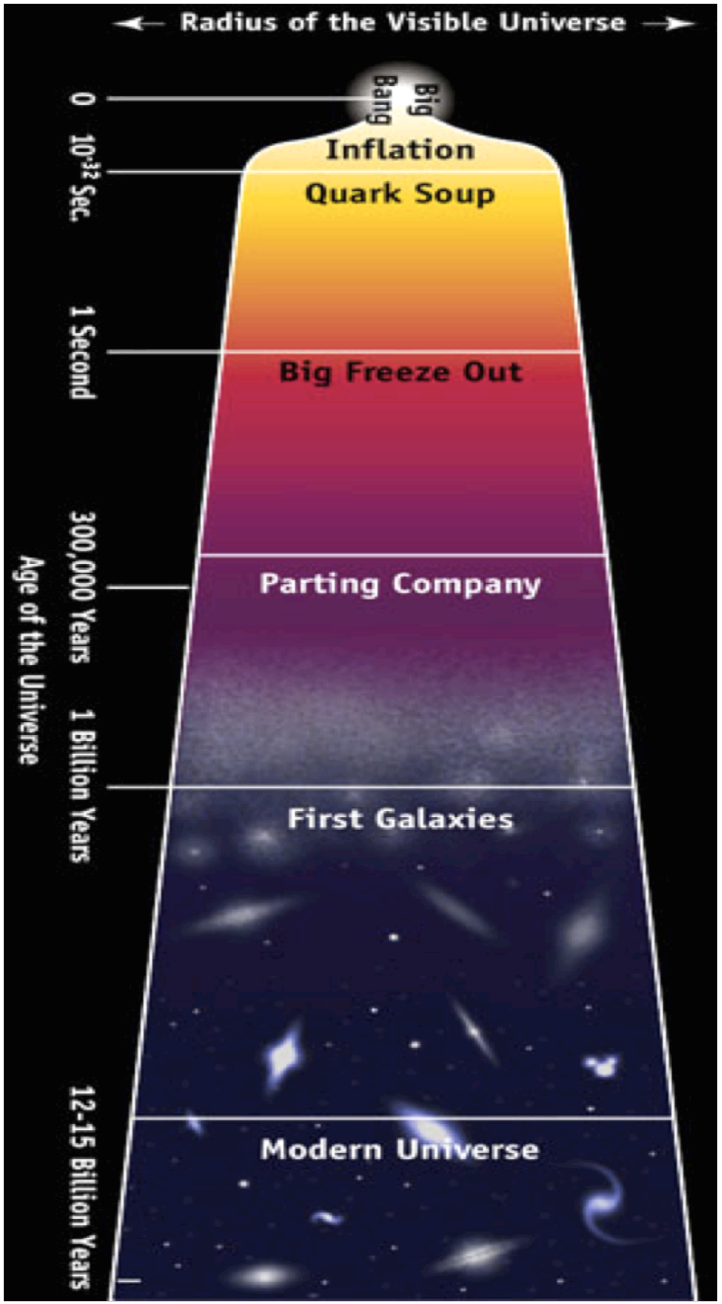

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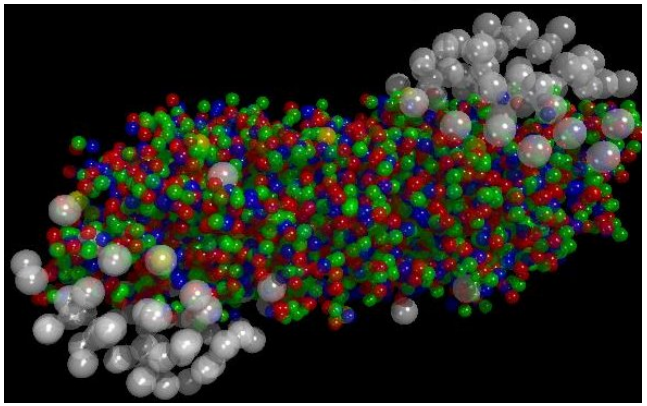

… this should recreate a state of matter in which hadrons 'dissolve' to produce a soup of unbound quarks and gluons (a 'Quark-Gluon Plasma')

… recreating conditions that last existed around 10^{-6} seconds after the big bang
… when the temperature of the universe was ~10^{13} ^{o}C!

Something to take away & think about …

What will a talk like this be like in 5 or 10 years time?

… my guess is it will contain answers from the LHC to some of the big remaining mysteries of the universe:

- Why does nature give us 3 generations of particles?
- Why are some particles more massive than others?
- Why is gravity so much weaker than the other forces?
- Why are the quarks and leptons so different?
- Are there new unknown particles and forces?
- Is there a deeper level of structure?
- Is the universe more than 3 dimensional?

Hopefully it will be as surprising to me as it is to you!

[Thanks to many Birmingham,. H1 & ATLAS and other colleagues, especially David Evans, Ian Kenyon, Max Klein, Peter Watkins]