Introduction to particle physics

Trygve Buanes

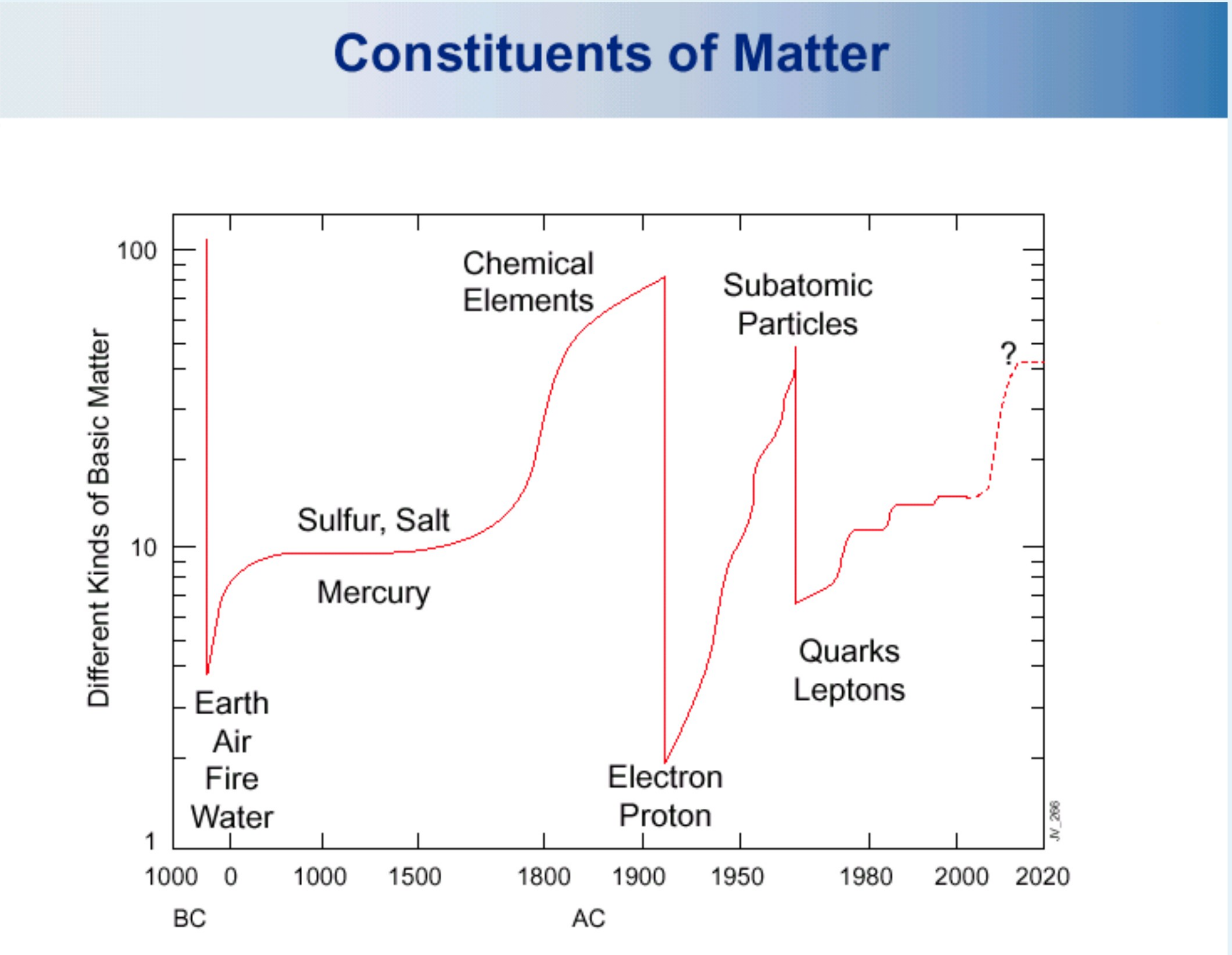
Natural units

- There is large freedom in selecting a system of units
  - Length: metres, feet, miles, ...
  - Energy: joule, erg, kwh, ...
- In particle physics one usually use **natural units**
  - System of units chosen such that $\hbar=c=1$
  - In natural units:
    - mass ~ energy
    - momentum ~ energy
    - length ~ energy^{-1}
    - time ~ energy^{-1}

Outline

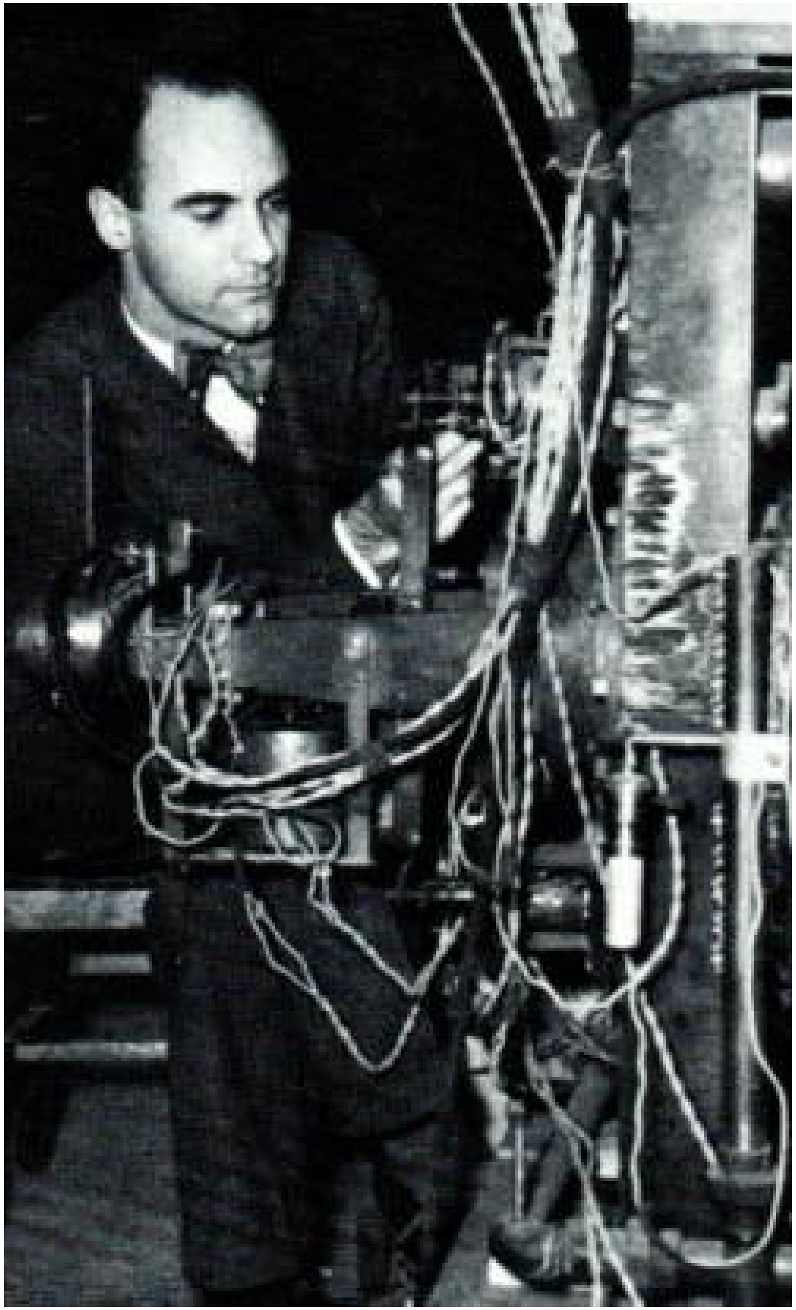
- A brief history of particle physics
- Understanding the underlying system
- Feynman diagrams
- The standard model
- Beyond the standard model
- From collisions to physics results

Fundamental building blocks through the history



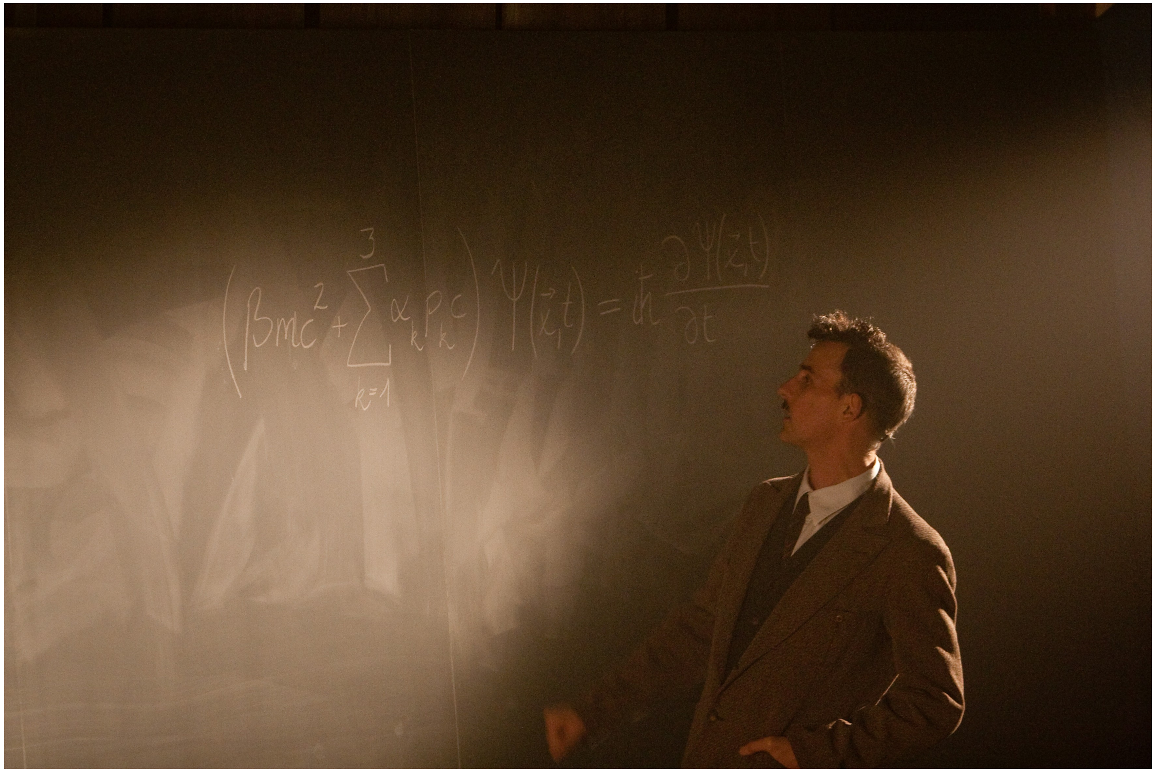
The first fundamental particles

- 1897: Thomson discovers the **electron**
- 1905: Einstein discovers the **photon**
- 1919: Rutherford discovers the **proton**
- 1932: Chadwic discovers the **neutron**



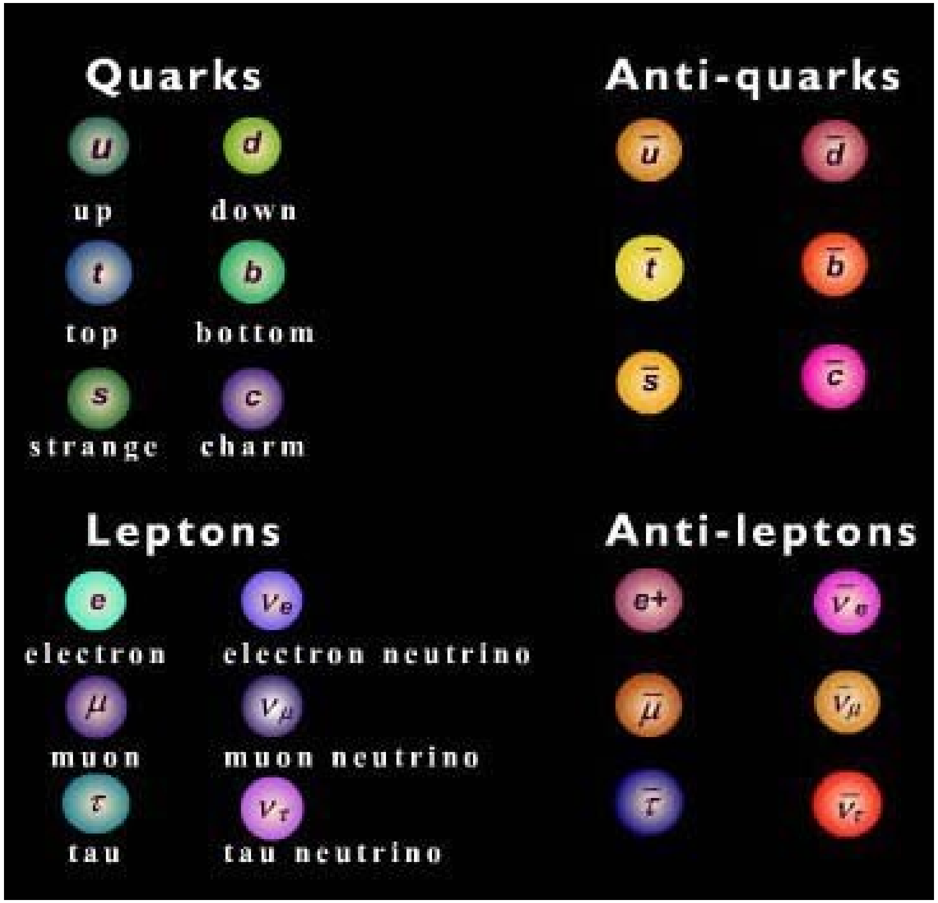
Antimatter

- Trying to unify quantum mechanics and relativity Dirac discovered that the equation describing the electron had an extra solution
    - **positrons**
- The prediction was soon confirmed experimentally
    - 1929: Skobeltsyn observes “positive electrons”
    - 1932: Anderson discovers the **positron**



Antimatter

- All particles have an associated anti-particle (some particles are their own anti-particle)
- Anti-particles has opposite quantum numbers compared to the particles
- When a particle meets its anti-particle, they annihilate
  - mass transformed to energy
- Anti-particles can form anti-atoms etc.

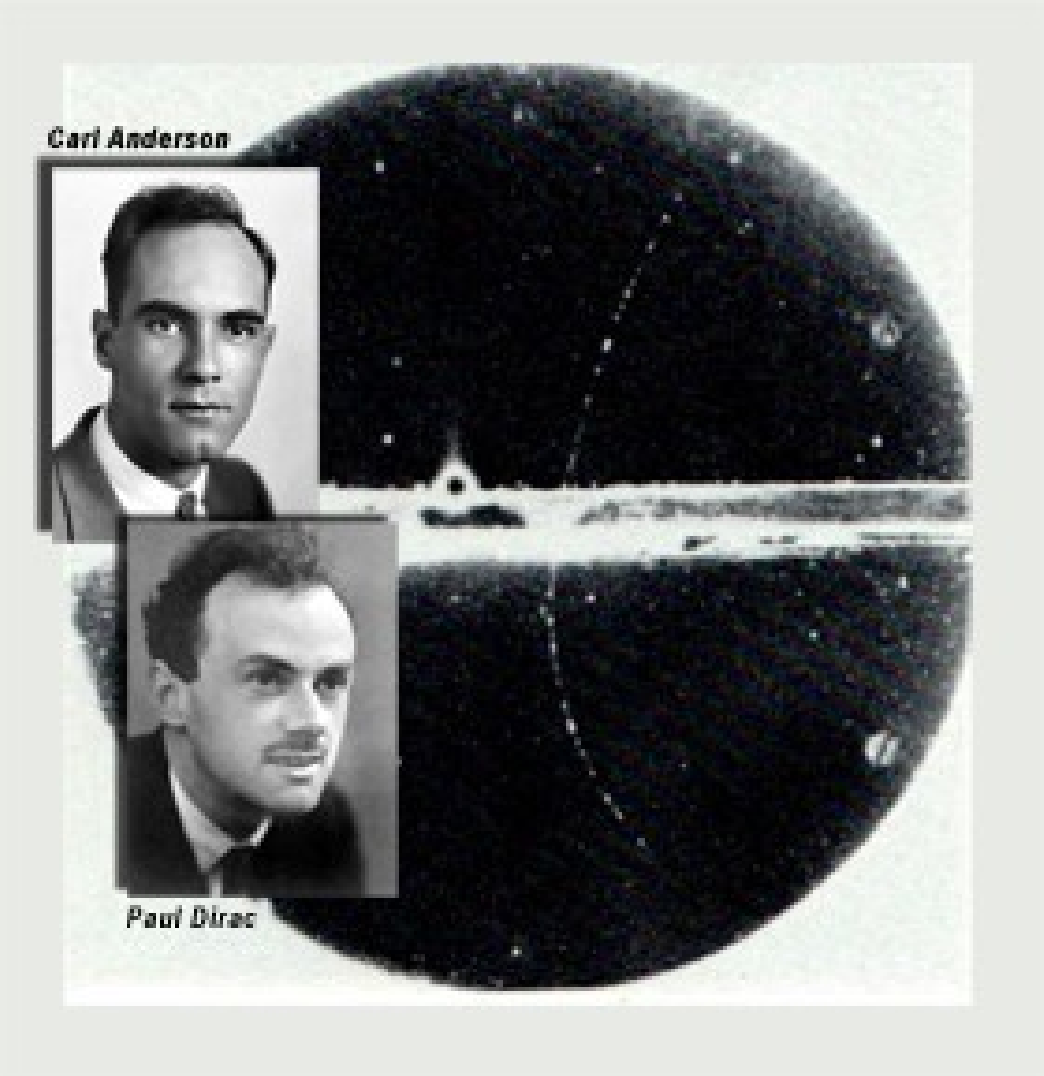


Radiation from above

- At first particle physics was mainly approached using radioactive materials
- Measuring the background radiation as a function of height and over sea indicated that there had to be other radiation source than radioactive earth
- In 1912 Hess measured the radiation at large altitude leading to the conclusion that the atmosphere is penetrated by radiation from outer space

Radiation from above

- Cosmic radiation proved to be an excellent “laboratory” for high energy physics
- Several new particles was identified in the cosmic radiation
- The positron was the first particle to be discovered this way



Who ordered that?

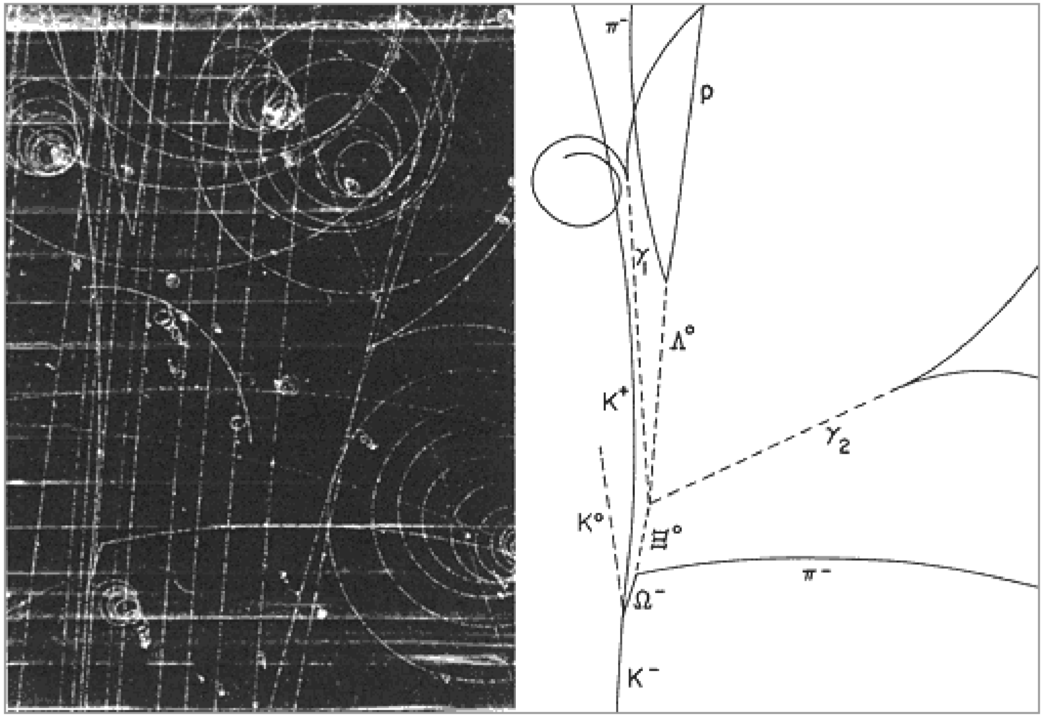
- By the mid 1930ies all particles needed to build the world we see was found
- The photon was accepted as carrying the electromagnetic force, and the search for the carrier of the strong force was ongoing
- A particle which seemed to have the correct mass was found, but somehow it didn't really fit in
  - The **muon** was discovered, and no-one understood why it was there

Collision machines

- Cosmic radiation gave the research a boost, but has its drawbacks
    - you don't know where a collision will happen
    - collisions are in a place where you cannot easily place detectors (top of atmosphere)
    - you cannot choose the energy of the collision
- Having machines accelerating particles yields much more flexibility

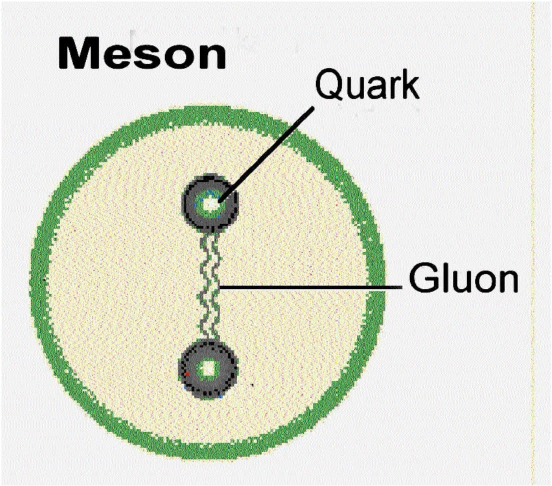
Collision machines

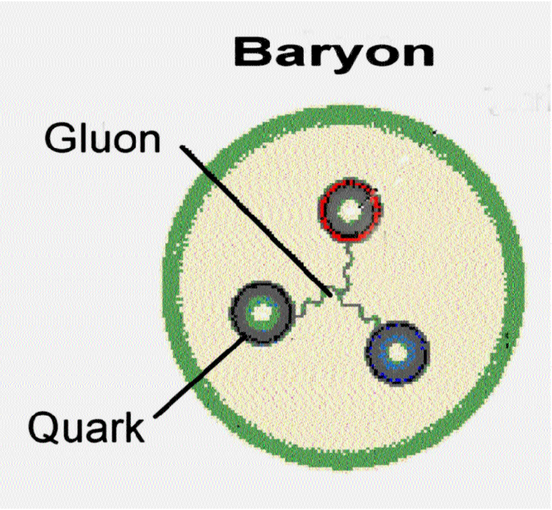
- With every generation of new accelerators, more and more particles were discovered
- Due to the large number of particles, people started to look for the underlying structure
    - analogous to the periodic system
- The idea of a number of quarks which could be combined in different ways was put forward in the 60ies



Making a system

- Leptons (electron, muon, neutrino...)
  - considered elementary
  - interacts through the weak and electromagnetic (if charged) interactions
  - may be stable or unstable
- Mesons
  - consists of quark and an antiquark
  - interacts through all forces
  - all are unstable
- Baryons
  - consists of three quarks
  - interacts through all forces
  - may be stable or unstable



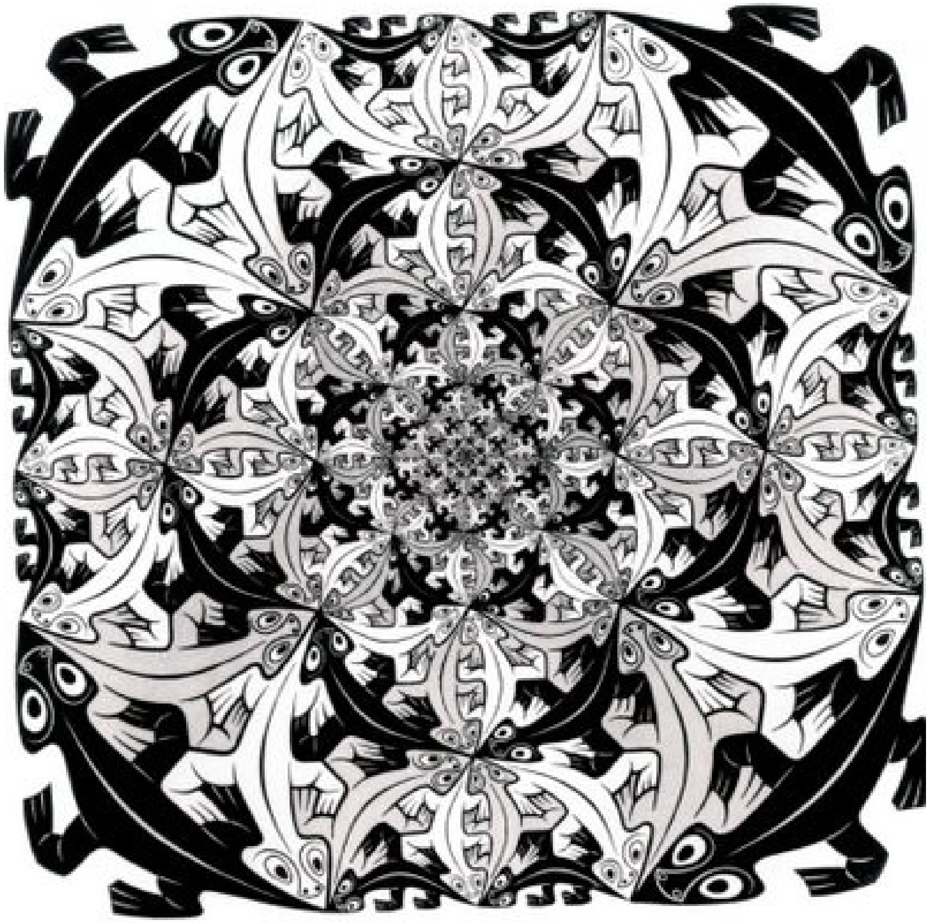


Conservation laws

	Quantised?	Consecequence	
Energy	No	A particle cannot decay to particles with more energy than the decaying particle	
Momentum	No	A particle cannot decay into less than two particles	
Angular momentum	Yes	Sum of spins and oribtal angular momentum must be the same before and after decay	
Charge	Yes	Charge must be the same before and after decay	

Symmetries

- A physical law is symmetric under a **transformation** if the physical measurable is not affected by the transformation
  - A quadrate does not change when rotated through 90°
  - A circle does not change when rotated through an arbitrary angle



Symmetries and conservation laws

- Noethers theorem:

  For each continuous symmetry, there is an associated conservation law

- By identifying all symmetries in a theory we can find all the conserved quantities

or

- By observing which conserved quantities are present, we can find out which symmetries should be built into the theory

Conservation laws

Conserved quant.	Quantised?	Consecquence	Symmetry
Energy	No	A particle cannot decay to particles with more energy than the decaying particle	No change in **time**
Momentum	No	A particle cannot decay into less than two particles	No change from **translation**
Angular momentum	Yes	Sum of spins and oribtal angular momentum must be the same before and after decay	No change when **rotated**
Charge	Yes	Charge must be the same before and after decay	No change from a **gaugetransformation**

Almost-symmetries

- Some hadrons was observed to live much longer than others
- Hadrons with long lifetime was called “strange”
- The long lifetime is ascribed to an imperfect symmetri called **strangeness**
- Strangeness is related to a symmetry respected by the strong and electromagnetic forces, but not by the weak

STRANGE QUARK s

The 2nd generation of down quark, **STRANGE QUARK** weighs about the same as a muon and was discovered in 1968.

Acrylic felt with poly bead fill for medium mass.

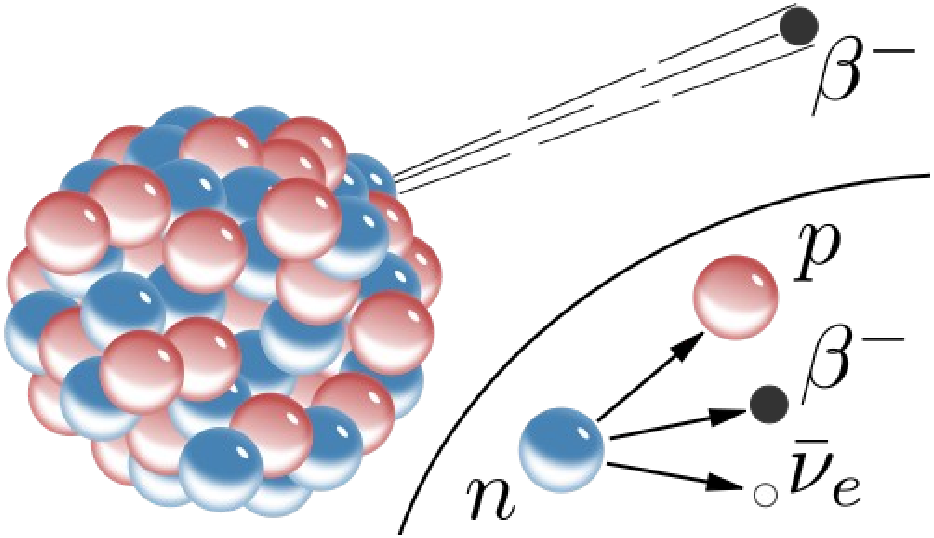
$9.75 PLUS SHIPPING

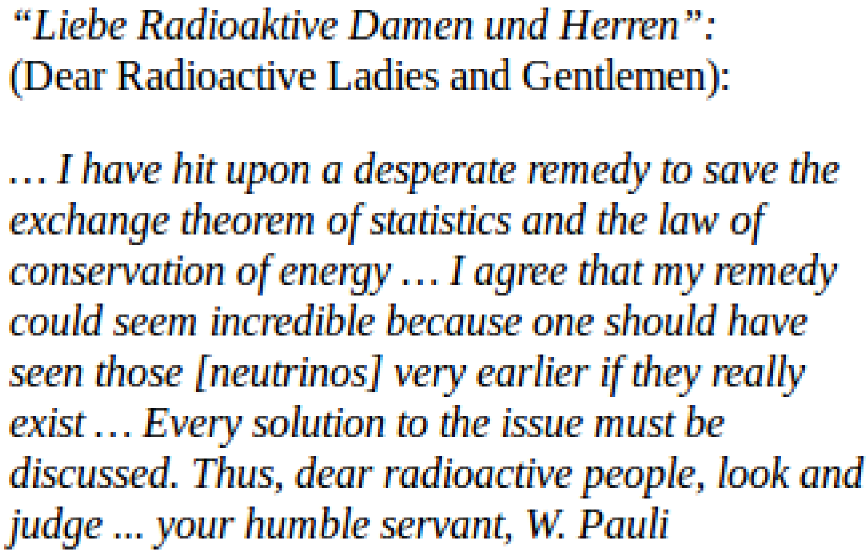
●●●●●●●○○○○○○

The PARTICLE ZOO

The neutrino and conservation of momentum

- In a β-decay, a nucleus spits out an electron
- Even if we start with identical nuclei, the energy of the emitted electron varies
- Apparently energy and momentum isn't conserved
- Pauli propsed that there had to be another, unobserved particle coming from the decay

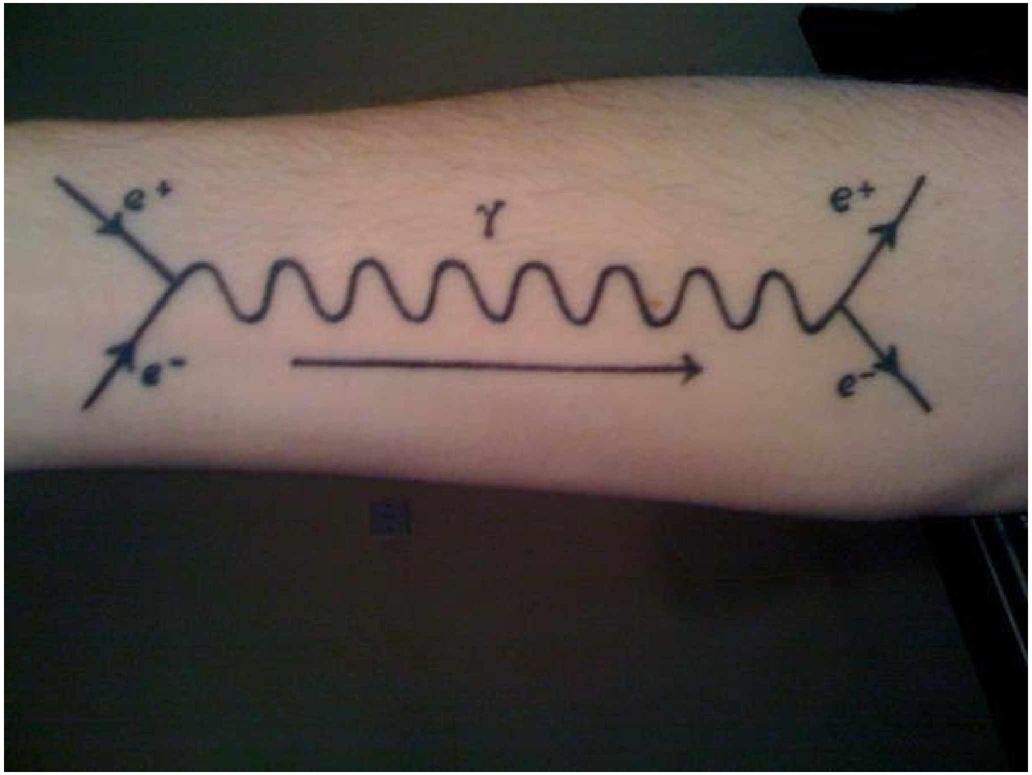



"Liebe Radioaktive Damen und Herren":
(Dear Radioactive Ladies and Gentlemen):

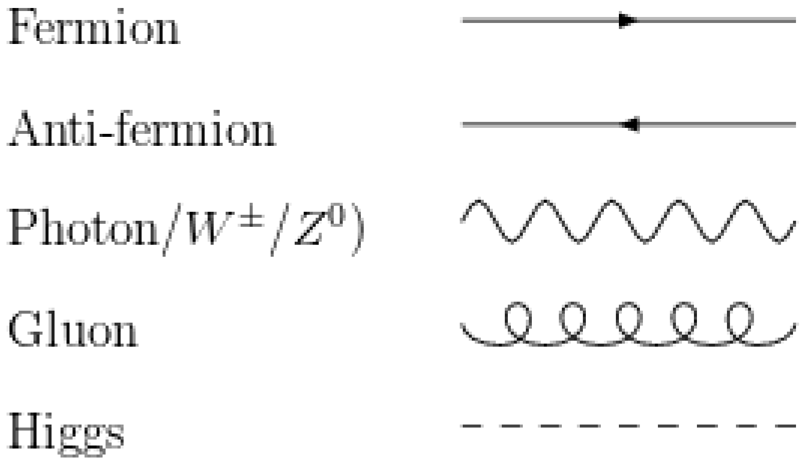
… I have hit upon a desperate remedy to save the exchange theorem of statistics and the law of conservation of energy … I agree that my remedy could seem incredible because one should have seen those [neutrinos] very earlier if they really exist … Every solution to the issue must be discussed. Thus, dear radioactive people, look and judge ... your humble servant, W. Pauli

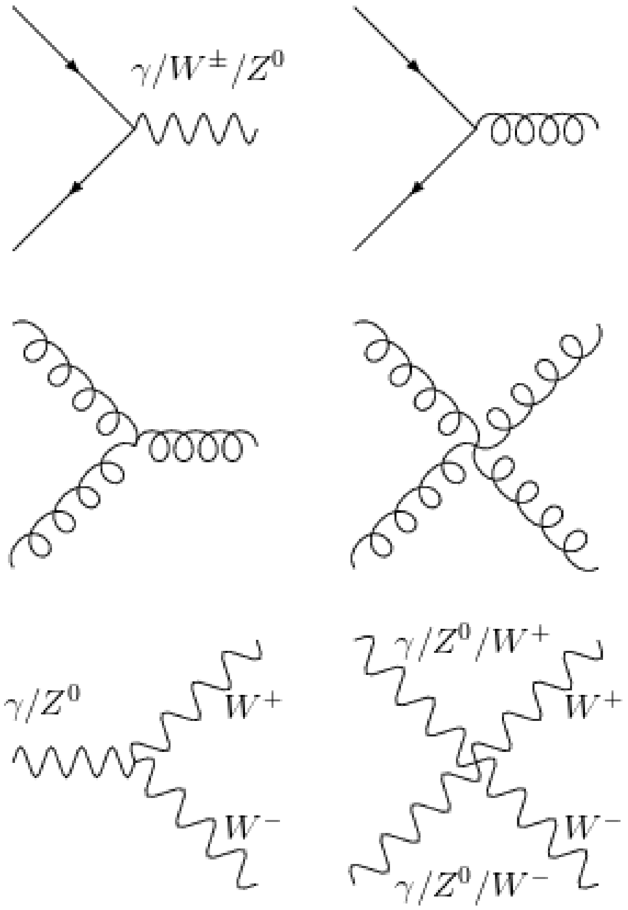
Feynman diagrams

- Pictograms showing particles and forces
- The diagrams has a one-to-one relation to parts in an integral equation used to calculate the probability for the process
- Useful to get an overview of what is going on (but don't take it to literally)



Elements of Feynman diagrams

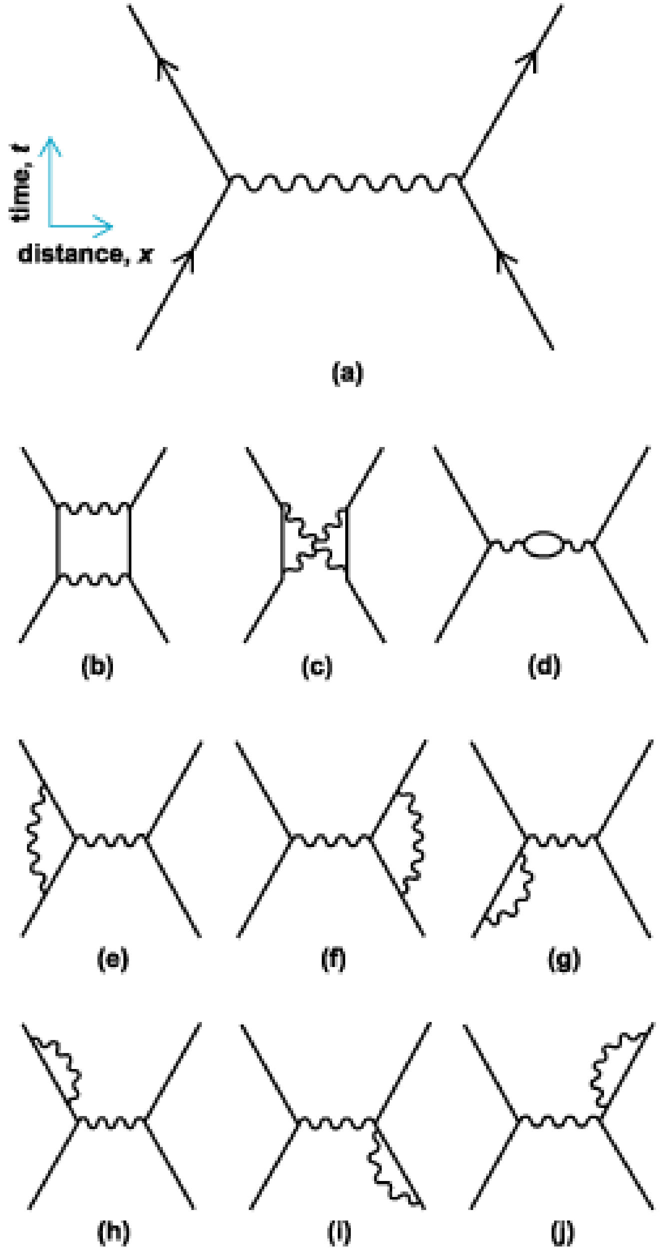




Feynman diagrams

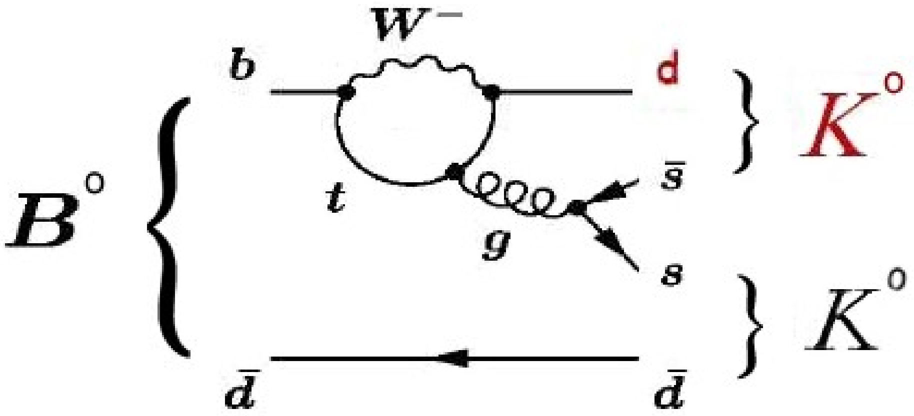
- Many particle physics processes can be calculated perturbatively
  - Low energy strong-force processes are an important exception

- Perturbation expansion organised by drawing Feynman diagrams with different number of loops



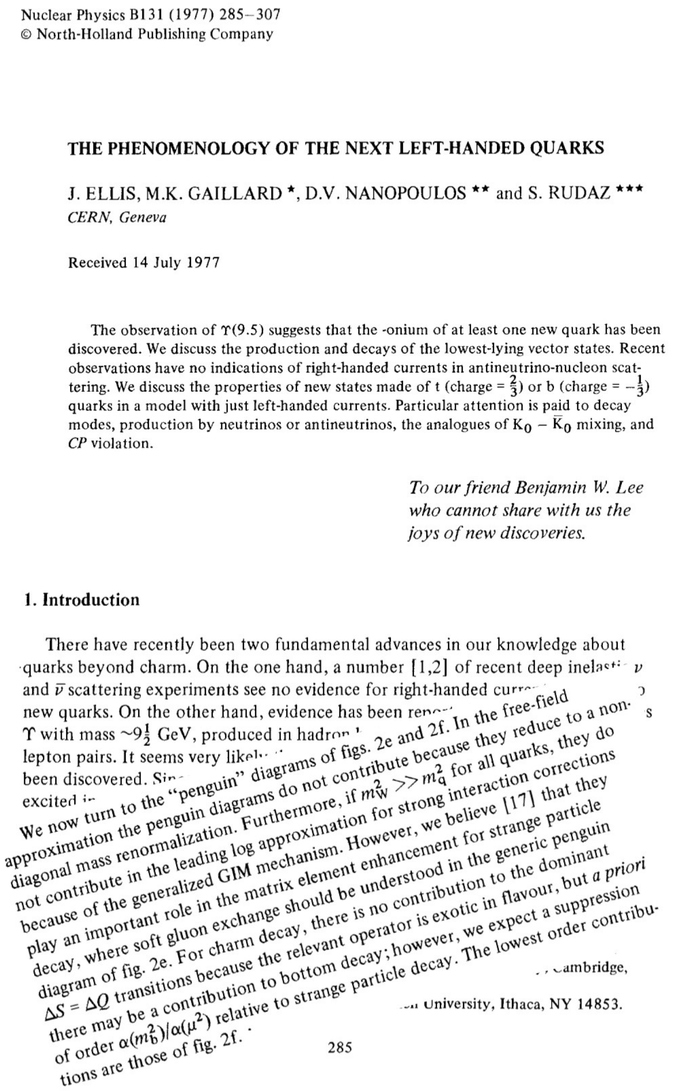
Penguin diagrams

- A particular class of loop diagrams are known as penguin diagrams



Penguin diagrams

- A particular class of loop diagrams are known as penguin diagrams
- The name penguin diagram was introduced by Ellis et al in 1977



Nuclear Physics B131 (1977) 285–307
© North-Holland Publishing Company

THE PHENOMENOLOGY OF THE NEXT LEFT-HANDED QUARKS

J. ELLIS, M.K. GAILLARD *, D.V. NANOPOULOS ** and S. RUDAZ ***
CERN, Geneva

Received 14 July 1977

The observation of $\Upsilon(9.5)$ suggests that the -onium of at least one new quark has been discovered. We discuss the production and decays of the lowest-lying vector states. Recent observations have no indications of right-handed currents in antineutrino-nucleon scattering. We discuss the properties of new states made of t (charge = $\frac{2}{3}$) or b (charge = $-\frac{1}{3}$) quarks in a model with just left-handed currents. Particular attention is paid to decay modes, production by neutrinos or antineutrinos, the analogues of $K_0 - \bar{K}_0$ mixing, and *CP* violation.

To our friend Benjamin W. Lee
who cannot share with us the
joys of new discoveries.

1. Introduction

There have recently been two fundamental advances in our knowledge about quarks beyond charm. On the one hand, a number [1,2] of recent deep inelas
and $\bar{\nu}$ scattering experiments see no evidence for right-handed curr
new quarks. On the other hand, evidence has been rep
Υ with mass $\sim 9\frac{1}{2}$ GeV, produced in hadron
lepton pairs. It seems very likel
been discovered. Si
excited i

We now turn to the "penguin" diagrams of figs. 2e and 2f. In the free-field approximation the penguin diagrams do not contribute because they reduce to a non-diagonal mass renormalization. Furthermore, if $m_W^2 >> m_q^2$ for all quarks, they do not contribute in the leading log approximation for strong interaction corrections because of the generalized GIM mechanism. However, we believe [17] that they play an important role in the matrix element enhancement for strange particle decay, where soft gluon exchange should be understood in the generic penguin diagram of fig. 2e. For charm decay, there is no contribution to the dominant $\Delta S = \Delta Q$ transitions because the relevant operator is exotic in flavour, but *a priori* there may be a contribution to bottom decay; however, we expect a suppression of order $\alpha(m_b^2)/\alpha(\mu^2)$ relative to strange particle decay. The lowest order contributions are those of fig. 2f.

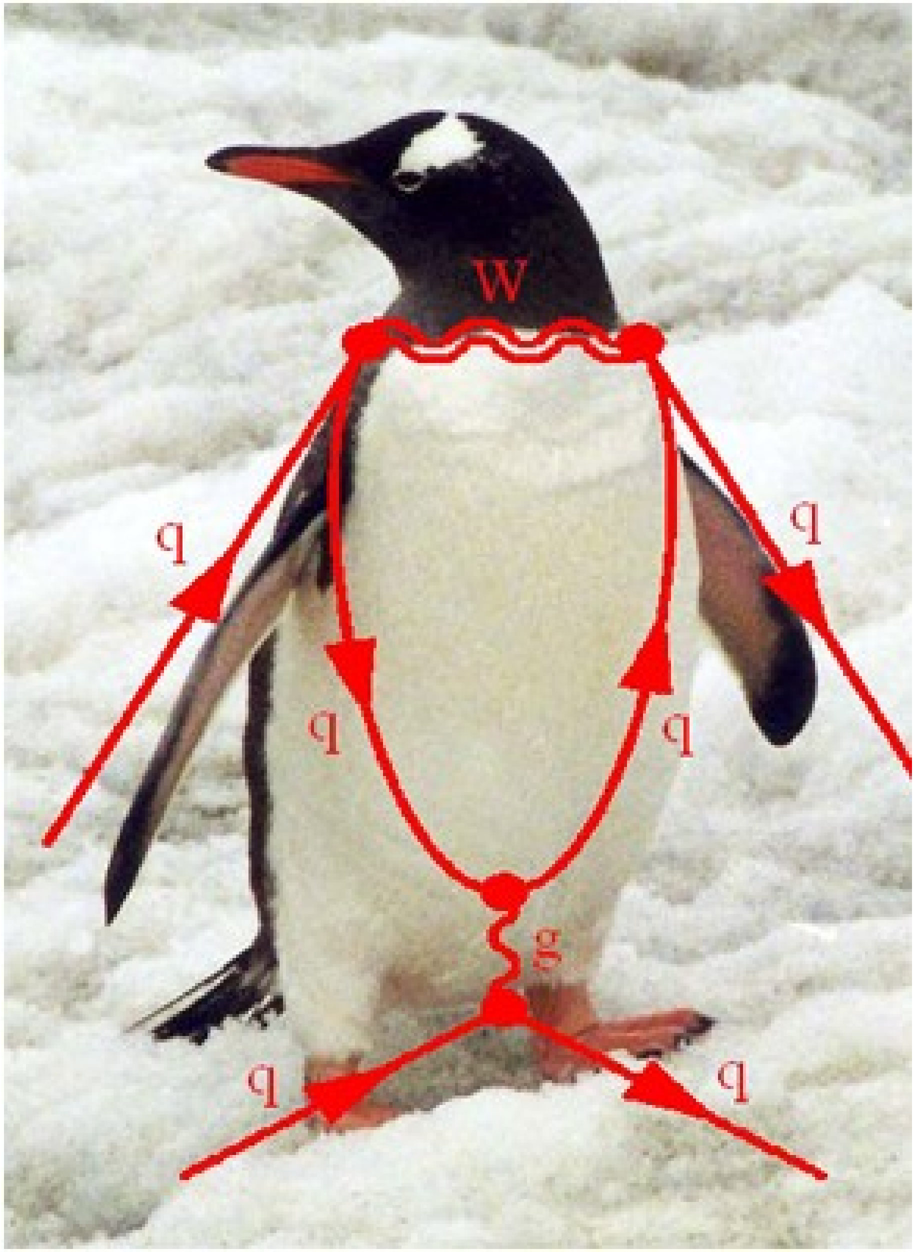
ambridge,

University, Ithaca, NY 14853.

285

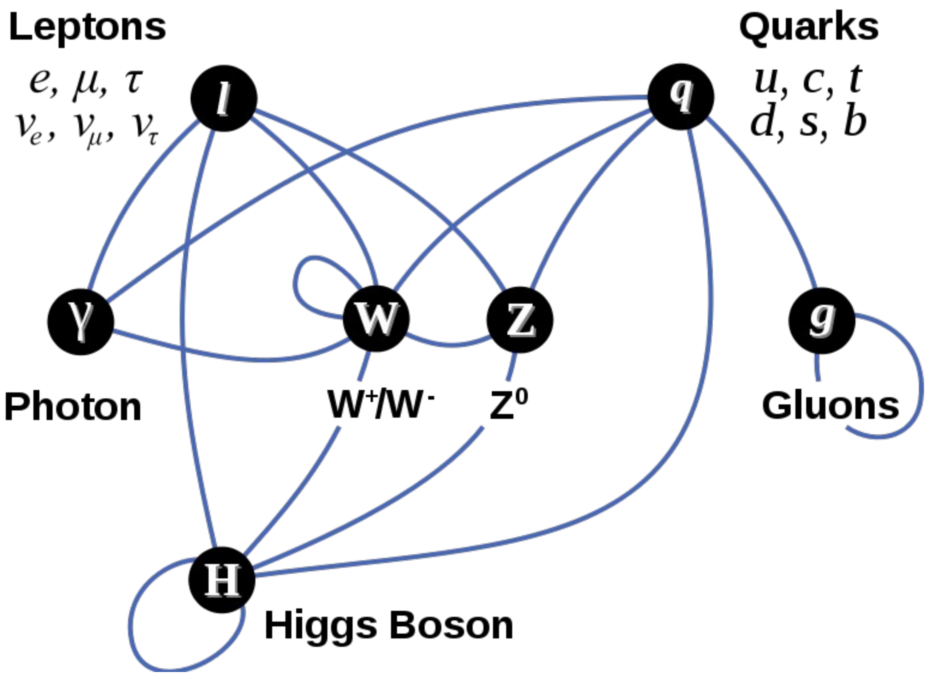
Penguin diagrams

- A particular class of loop diagrams are known as penguin diagrams
- The name penguin diagram was introduced by Ellis et al in 1977

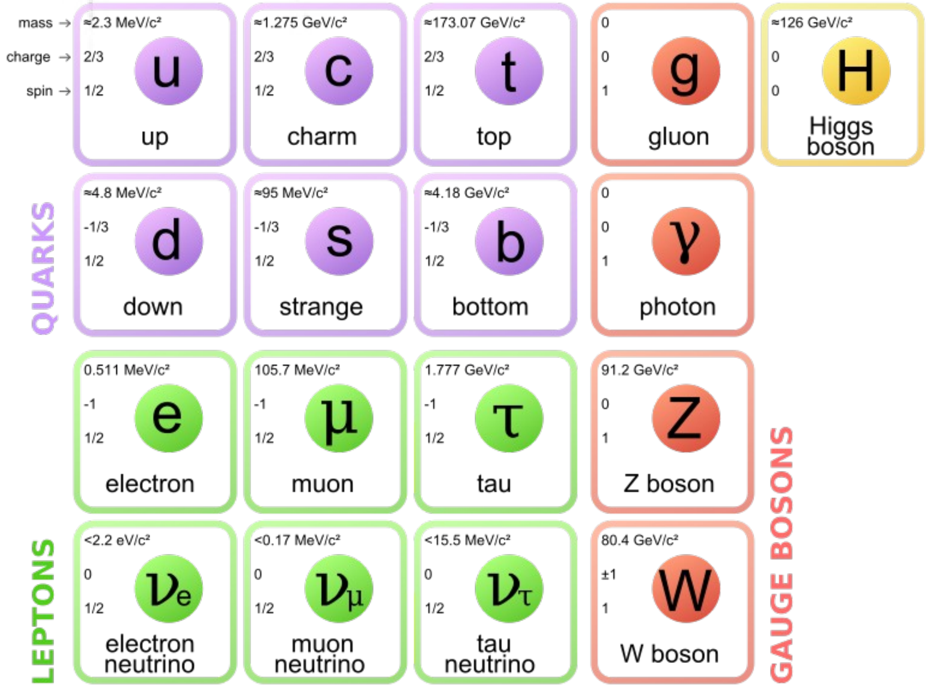


The standard model

- The standard model is a mathematical model that describes what we presently know about particle physics
- The model was formulated in the 1970'ies
- No experimental results from particle physics disagrees with the standard model
  - But there are astrophysical observations that shows that there is more to it



Particles in the standard model

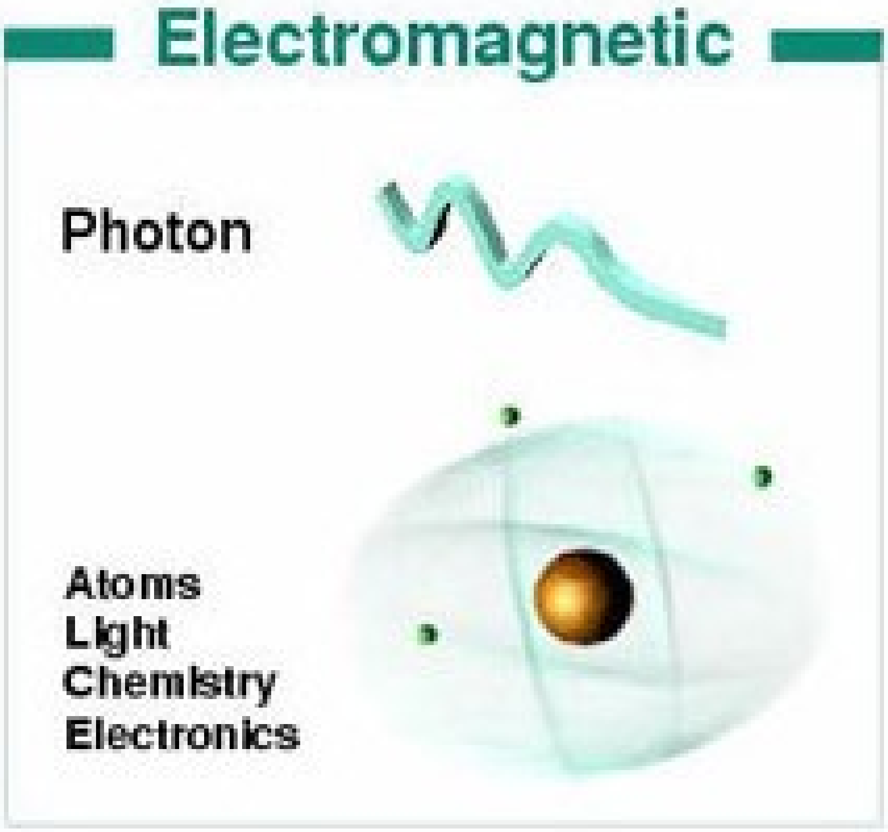


mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson	
QUARKS	≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon		
	0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson		GAUGE BOSONS
LEPTONS	<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson		

- Three generation of particles
- 12 matter particles (fermions)
  - 6 quarks
  - 6 leptons
- 4 force carrying particles (bosons)
- 1 particle related to the mechanism giving particles mass (boson)

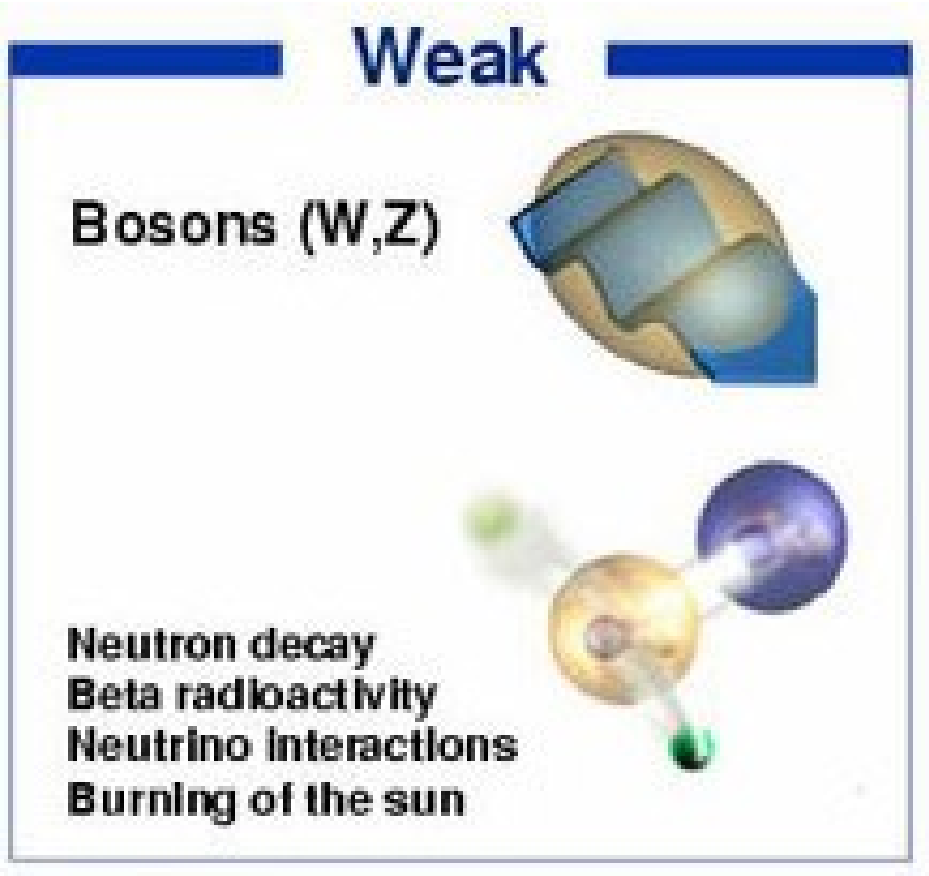
The electromagnetic force

- The electromagnetic force binds together electrons and nuclei into atoms
- The **photon** is the carrier of the force
- All particles with electric charge is affected
- Since the photon is massless, the range is infinite



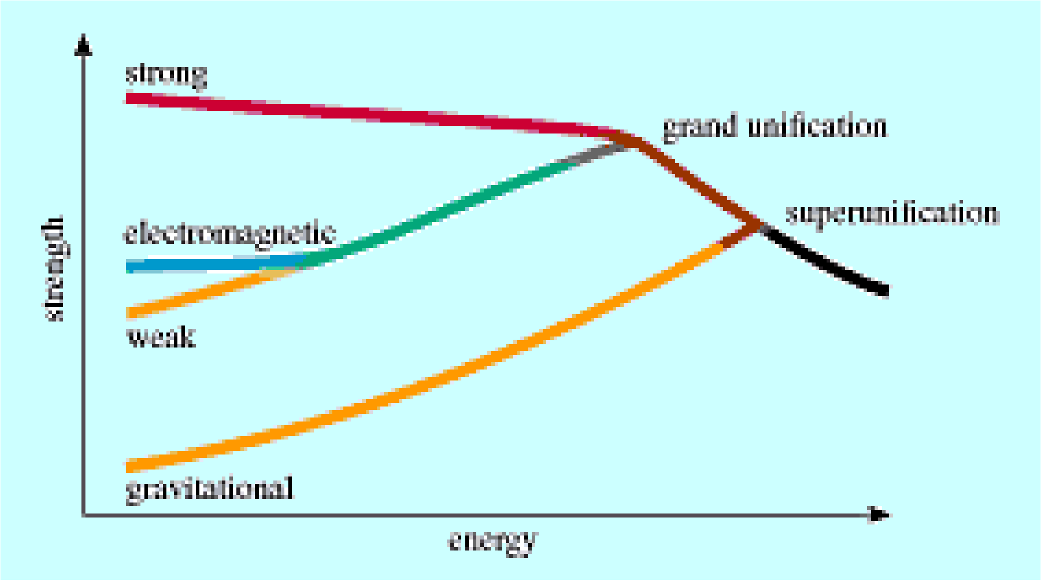
The weak force

- The weak force causes the decay of a number of particles
- The weak force is carried by three particles: **$W^{\pm}$**, **Z**
- Massive force carriers make the force have a very short range (~10^{-18} m)
- The weak force works all matter particles in the standard model

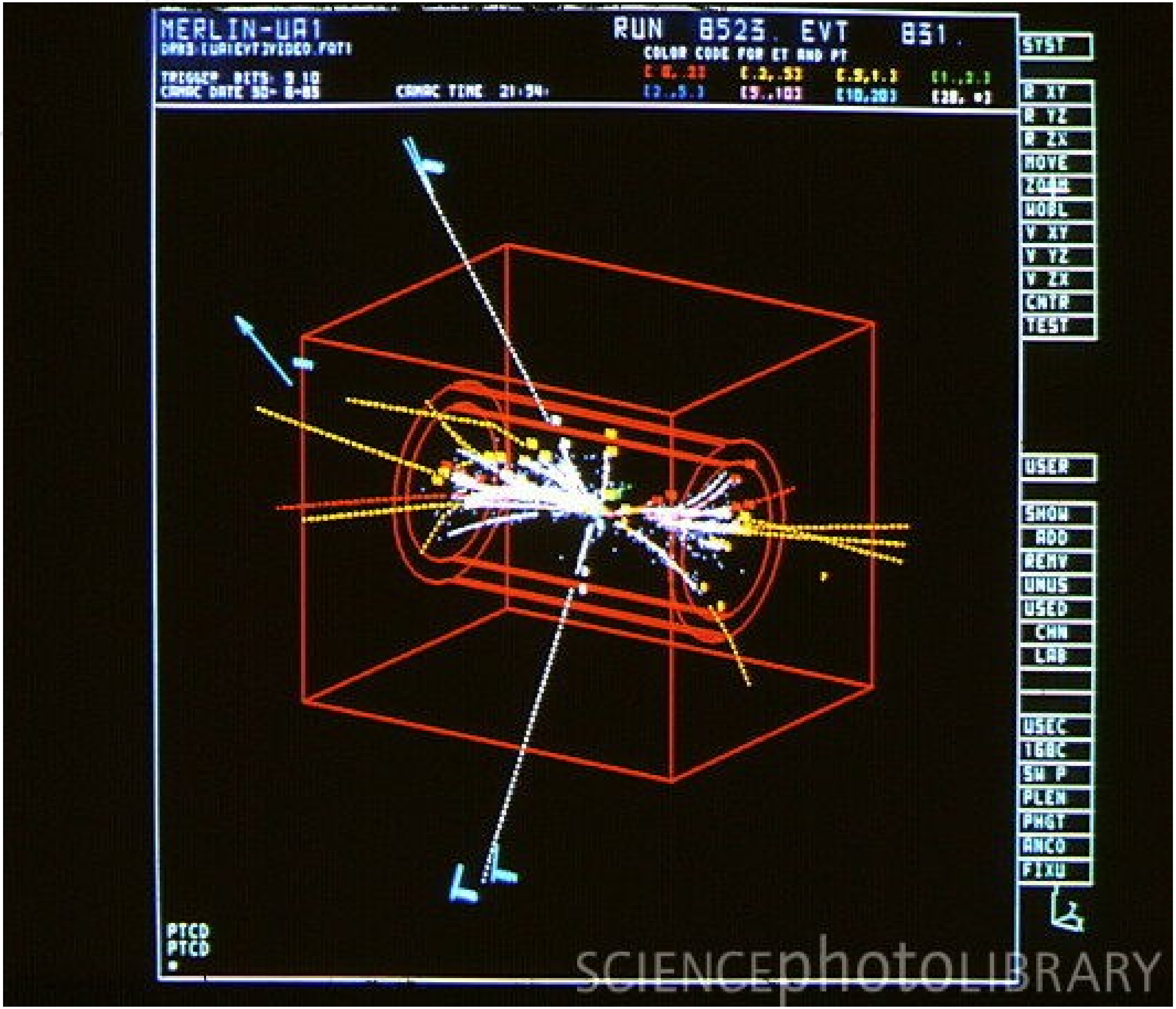


Electroweak unification

- Electromagnetism and weak force proves to be to aspects of the same force
- The constrast between the massive $W^{\pm}$ and Z, and the massless photon makes the forces very different at low energies
- At higher energies, the difference disappears
- Is there such a unification also for the other forces?



Discovery of the Z boson

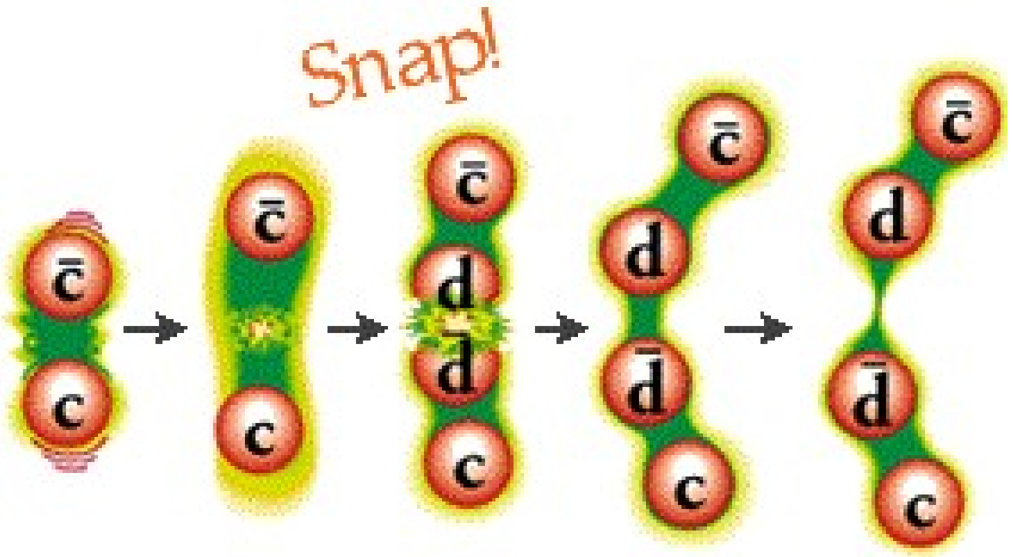


The strong force

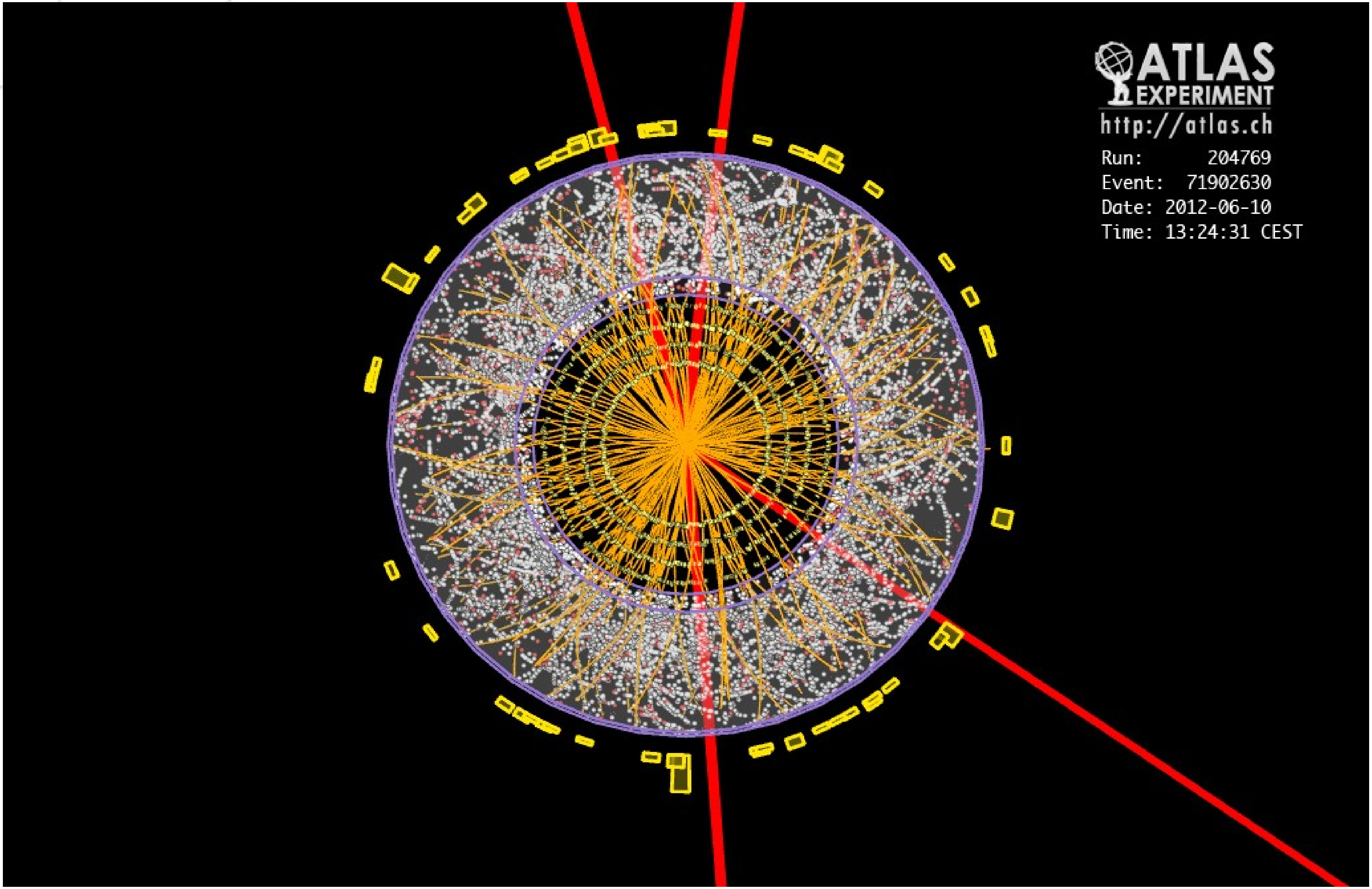
- The strong force binds quarks together into hadrons (and nucleons into nuclei)
- **Gluons** carries the strong force
- Gluons are massless, but the range is nevertheless very limited (~10^{-15}m) due to gluon-gluon interactions
- The strong force works on all particles with “colour charge”, i.e. quarks and gluons

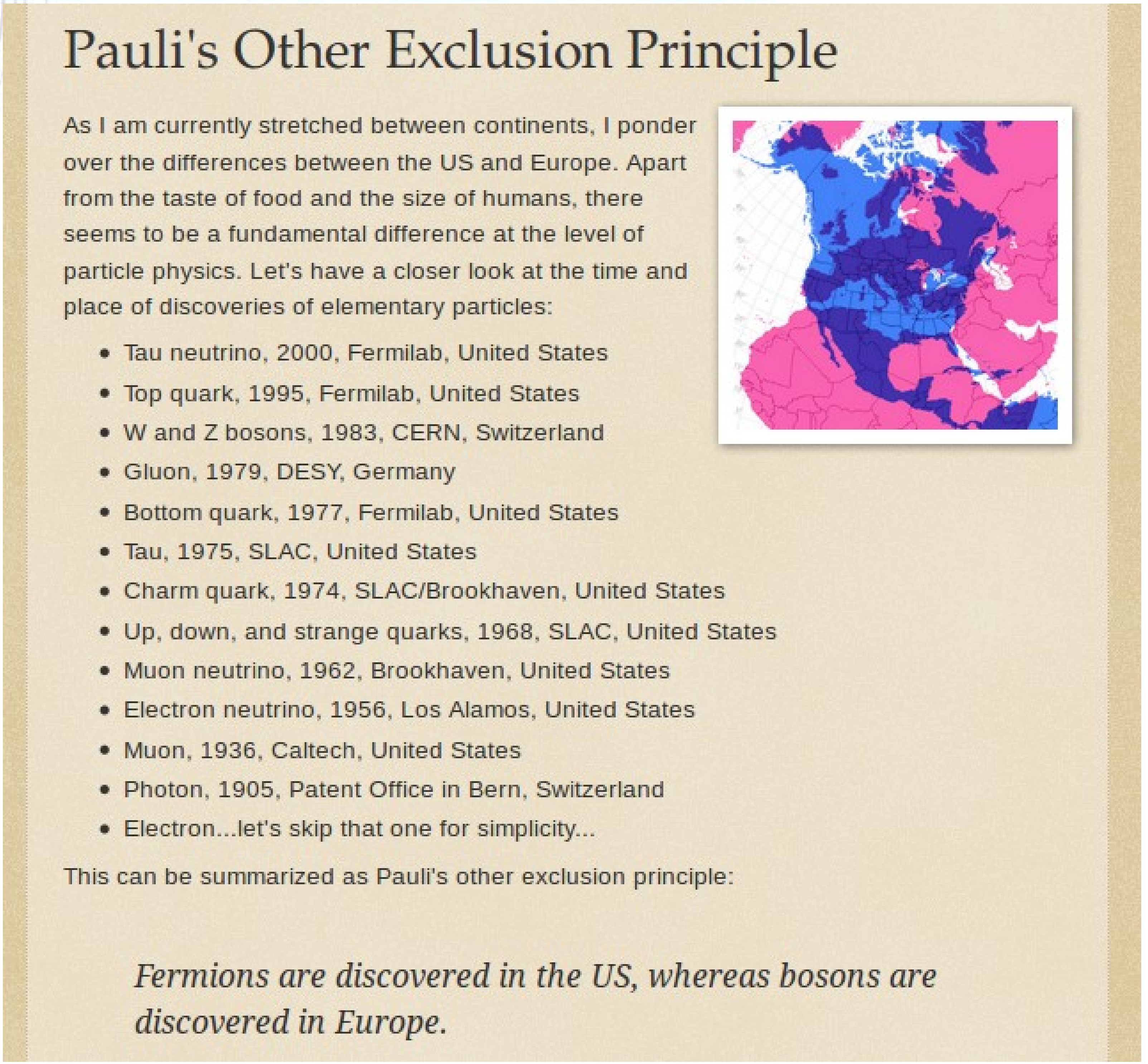
Confining colours

- Strong interactions grows stronger the further the colour charges are separated
- It is not possible to separate a quark or a gluon out of a hadron
- If enough energy is put into a hadron, the gluon field stretches out like a tube, and when it breaks a new quark-antiquark pair is created such that no free quarks are seen



The Higgs boson





Pauli's Other Exclusion Principle

As I am currently stretched between continents, I ponder over the differences between the US and Europe. Apart from the taste of food and the size of humans, there seems to be a fundamental difference at the level of particle physics. Let's have a closer look at the time and place of discoveries of elementary particles:

- Tau neutrino, 2000, Fermilab, United States
- Top quark, 1995, Fermilab, United States
- W and Z bosons, 1983, CERN, Switzerland
- Gluon, 1979, DESY, Germany
- Bottom quark, 1977, Fermilab, United States
- Tau, 1975, SLAC, United States
- Charm quark, 1974, SLAC/Brookhaven, United States
- Up, down, and strange quarks, 1968, SLAC, United States
- Muon neutrino, 1962, Brookhaven, United States
- Electron neutrino, 1956, Los Alamos, United States
- Muon, 1936, Caltech, United States
- Photon, 1905, Patent Office in Bern, Switzerland
- Electron...let's skip that one for simplicity...

This can be summarized as Pauli's other exclusion principle:

> *Fermions are discovered in the US, whereas bosons are discovered in Europe.*

Beyond the standard model

- The standard model is *not* the whole picture
  - No explanation for dark matter
  - No explanation for matter/anti-matter asymmetry
  - Neutrino masses may require non-trivial extension
  - Hierarchy problem
  - Unstable universe
  - Gravity not included
  - No explanation for dark energy

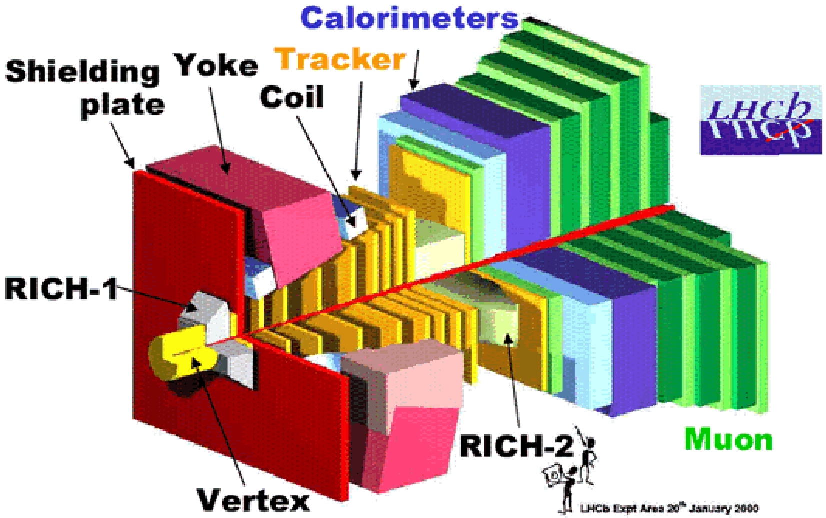
Dark matter

- 80% of the mass in the universe consists of particles that are not included in the standard model

- The extra mass is only observed gravitationally, but weak interactions are not ruled out
- Many popular models proposed to explain dark matter are testable at LHC

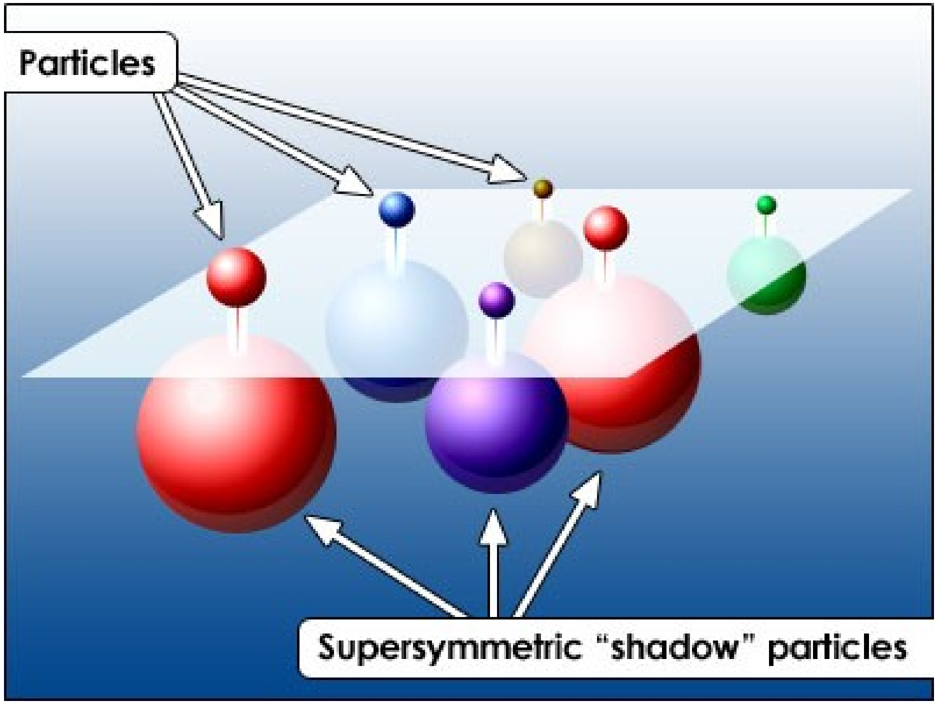
Matter/antimatter asymmetry

- There is a lot matter and almost no anti-matter in the universe
    - Either matter and anti-matter was created in unequal amounts, or annihilation treated matter and anti-matter asymetrically
    - For every 1 000 000 000 anti-matter particles, there were 1 000 000 001 matter particles
    - The weak force treat matter and anti-matter slightly differently, but the difference is too small to explain the asymmetry
- LHCb is a specialised experiment for studying B-physics
    - Most promising place to study CP-violation which is necessary to explain the asymmetry



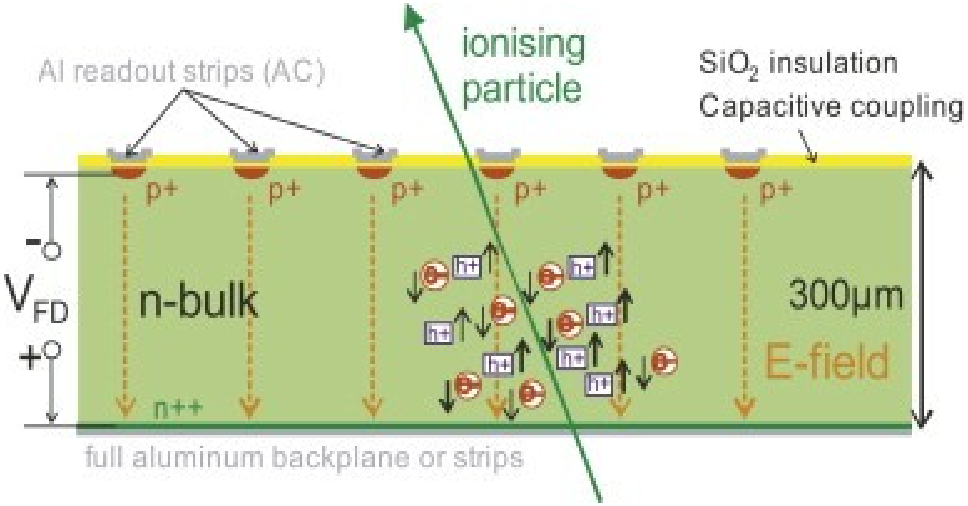
Supersymmetry (SUSY)

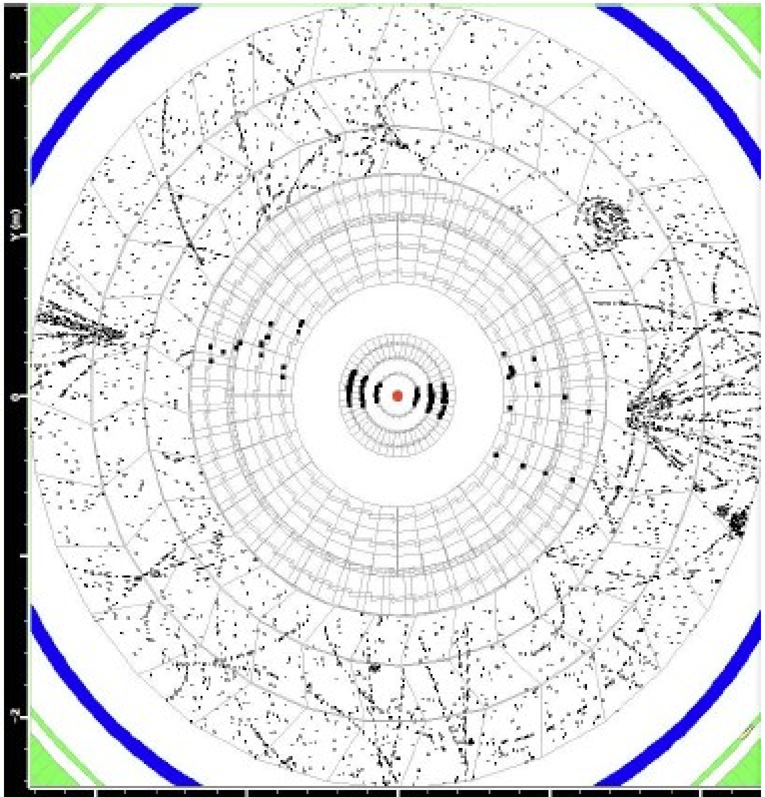
- SUSY is a symmetry which relates fermions and bosons
    - Predicts that all standard model particles has a partner with opposite statistics
- SUSY can solve (or at least reduce) the hierarchy problem if the SUSY mass scale is in LHC range
- Many SUSY models has an excellent dark matter candidate
    -



From collisions to physics results

- A particle passing through the detector creates localised charges which are read out
  - hits
- The different hits must be grouped into physics objects
  - tracking
  - jet reconstruction
- Physics objects are interpreted to understand the underlying physics



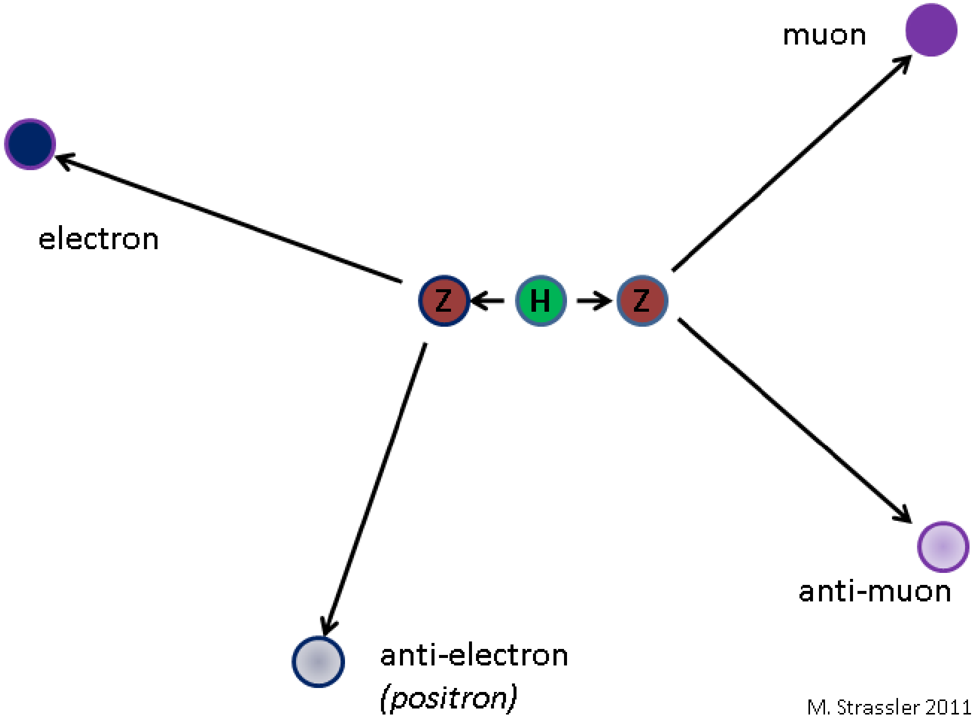


Triggering

- LHC collides protons every 50 ns
- Only ~100 events can be stored each second
- Based on hits or partially reconstructed events one decides which events to store
- The rest of the events are lost forever...

Finding a signal

- Typically one start from some model with certain predictions on what you should look after
  - resonances
  - high momentum particles
  - momentum imbalance
- Look through all recorded events and see if the recorded signature is there



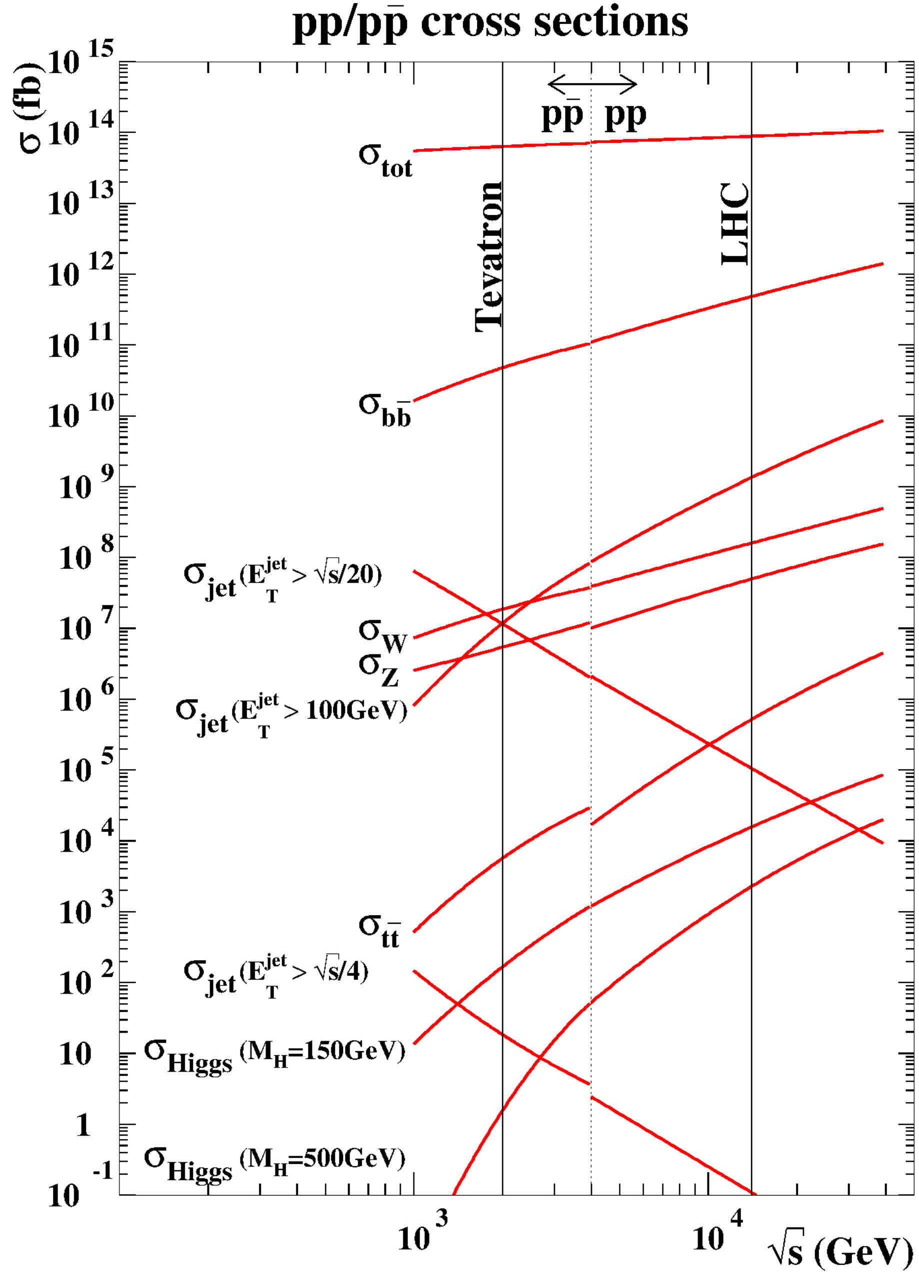
M. Strassler 2011

A small problem...

- All the easy things are done... Now we are challenging the difficult stuff
- Interesting processes generally constitutes a very small portion of the collisions
- We are not looking for a needle in a haystack...

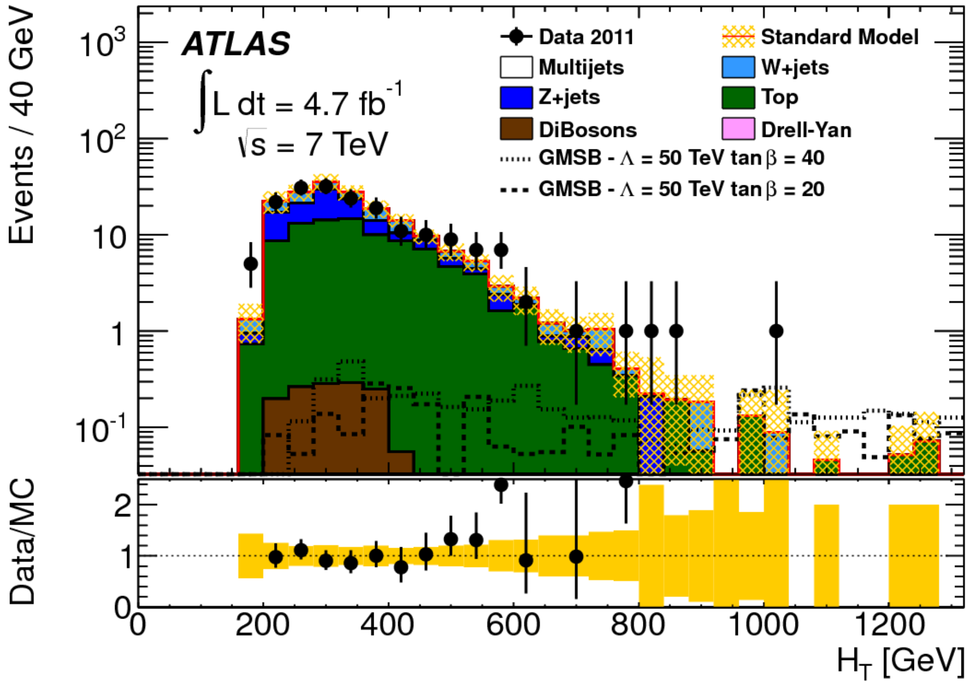
  not even a needle in a field of haystacks...

  we are looking for a rare kind of straw in a field of haystacks



Dealing with the background

- For most interesting signals, there are some “normal” processes which resembles the signal signature
    - intrinsically similar
    - imperfect detection
- By a clever choice of kinematic variables on can often reduce the background significantly
- The background needs to be measured with high accuracy to know if what we see is a signal or just “normal” processes cheating us



Statistical interpretation

- Important to quantify uncertainty in background (and signal) estimation
  - statistical
  - systematic
- Discovery?
  - how likely is it to observe at least this many events given the background estimation
- Limit?
  - how likely is it to observe no more than this number of events given the signal and background estimation