Introduction to Particle Physics and the Standard Model

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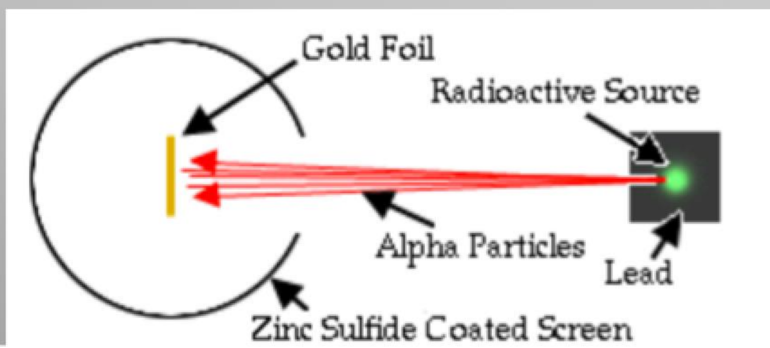
Aim of the Lectures

- What I plan to cover in the four lectures
  - The Standard Model: How did we get there (historical review). Some details on the Standard Model interactions
  - A short experimental introduction for today's accelerators modern experiments: Example case experiments at the LHC
  - Recent results on the searches beyond the Standard Model.
  - The Future
- This is an experimenter's view ☺

High Energy Physics Experiments

First High Energy Physics Experiments:

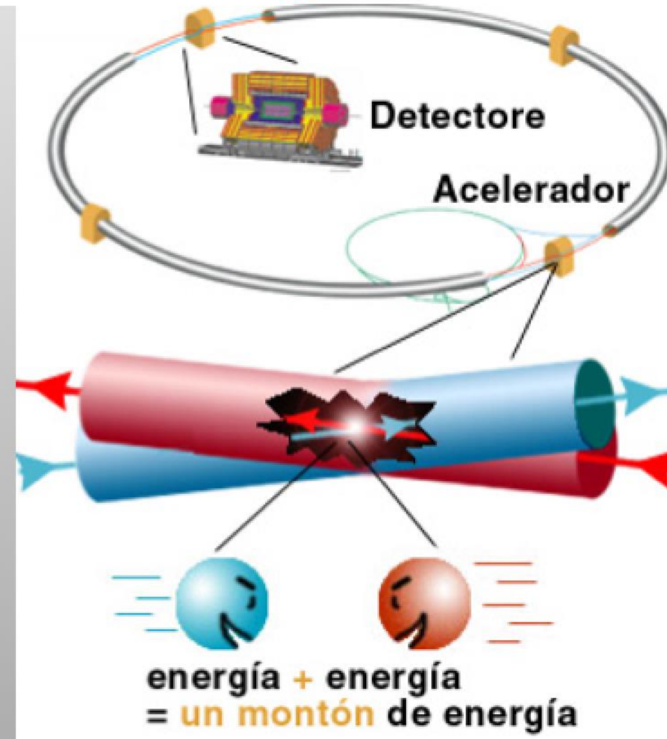
Beam on fixed target!



Rutherford experiment (1909)

High Energy Physics Experiments since mid 70's:

Colliding beams!

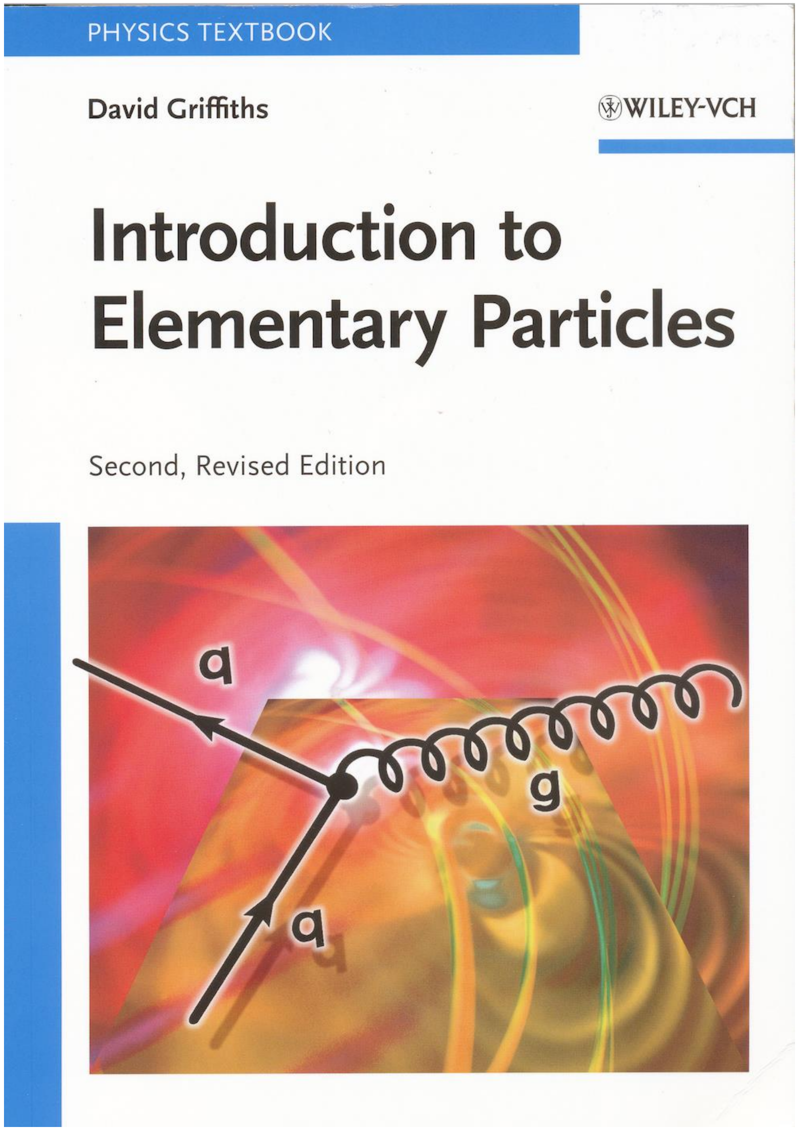


Centre of mass energy squared $s=2E_1m_2$

Centre of mass energy squared $s=4E_1E_2$

…plus secondary beams such as neutrinos…

Textbook for these Lectures:



Other recommended books

Quarks and Leptons
Halzen and Martin

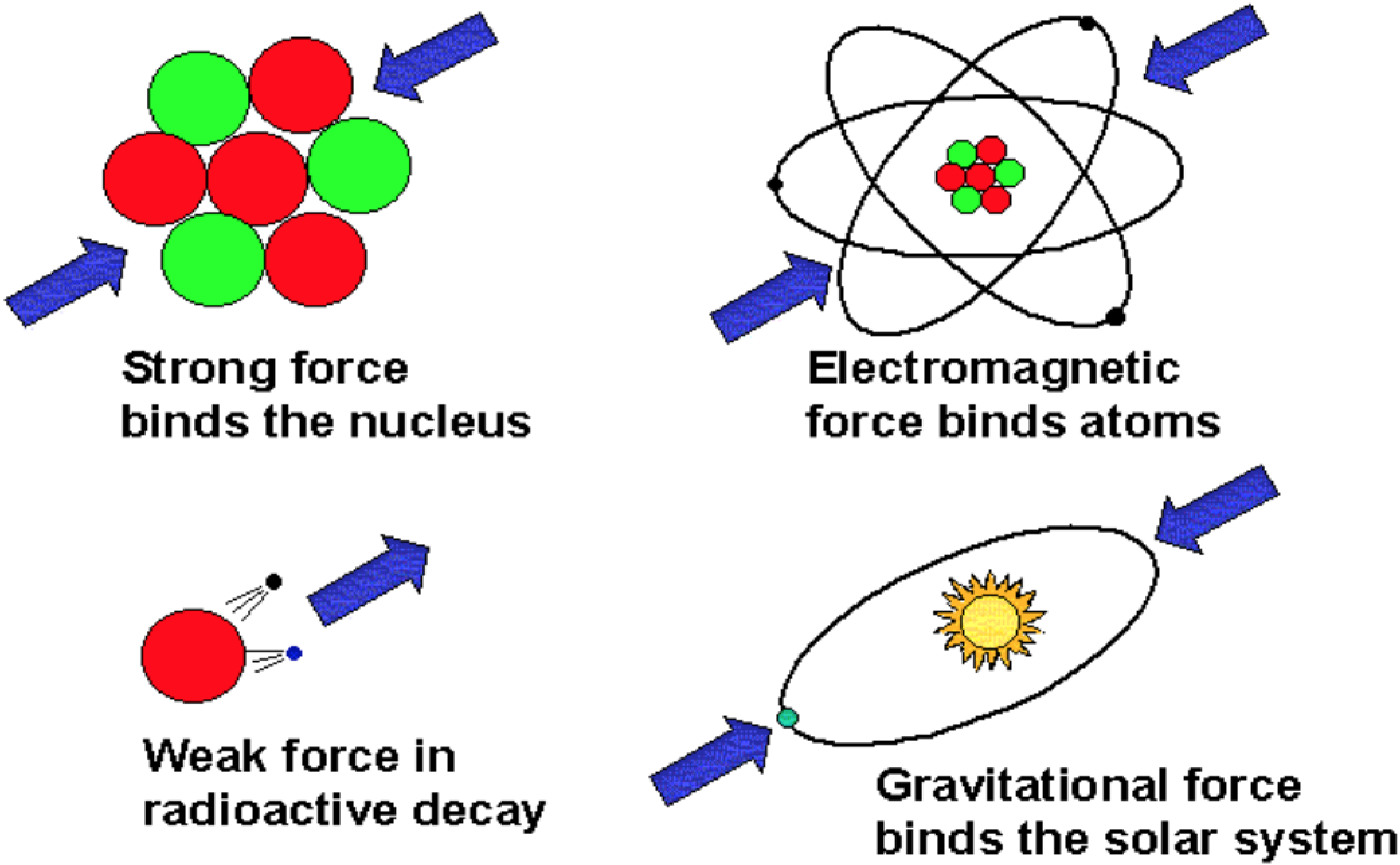
Particle Physics
Martin and Shaw

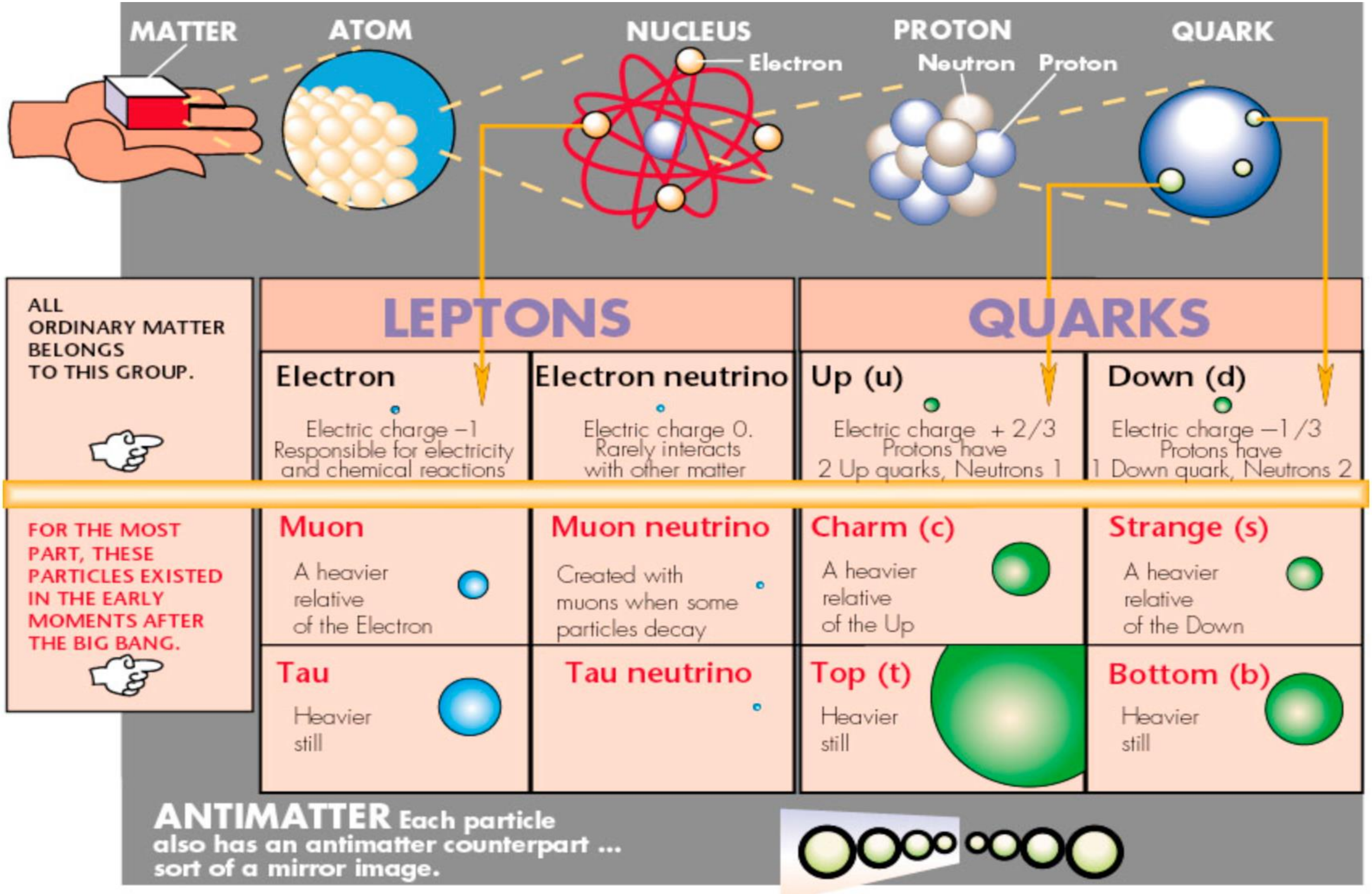
Modern Particle Physics (incl. Higgs)
Thomson

Gauge Theories in Particle Physics
Aitchison and Hey


What is the world made of?
What holds the world together?
Where did we come from?

The Fundamental Forces of Nature

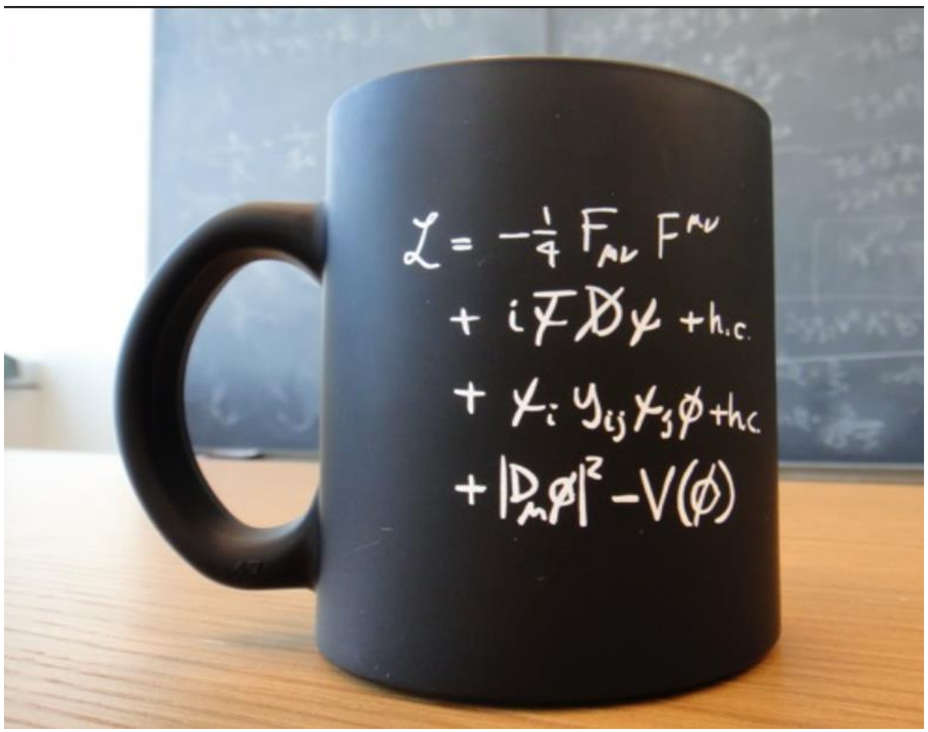



MATTER
ATOM
NUCLEUS
Electron
PROTON
Neutron
Proton
QUARK
ALL ORDINARY MATTER BELONGS TO THIS GROUP.
LEPTONS
QUARKS
Electron
Electric charge –1
Responsible for electricity and chemical reactions
Electron neutrino
Electric charge 0.
Rarely interacts with other matter
Up (u)
Electric charge + 2/3
Protons have 2 Up quarks, Neutrons 1
Down (d)
Electric charge –1/3
Protons have 1 Down quark, Neutrons 2
FOR THE MOST PART, THESE PARTICLES EXISTED IN THE EARLY MOMENTS AFTER THE BIG BANG.
Muon
A heavier relative of the Electron
Muon neutrino
Created with muons when some particles decay
Charm (c)
A heavier relative of the Up
Strange (s)
A heavier relative of the Down
Tau
Heavier still
Tau neutrino
Top (t)
Heavier still
Bottom (b)
Heavier still
ANTIMATTER Each particle also has an antimatter counterpart ... sort of a mirror image.

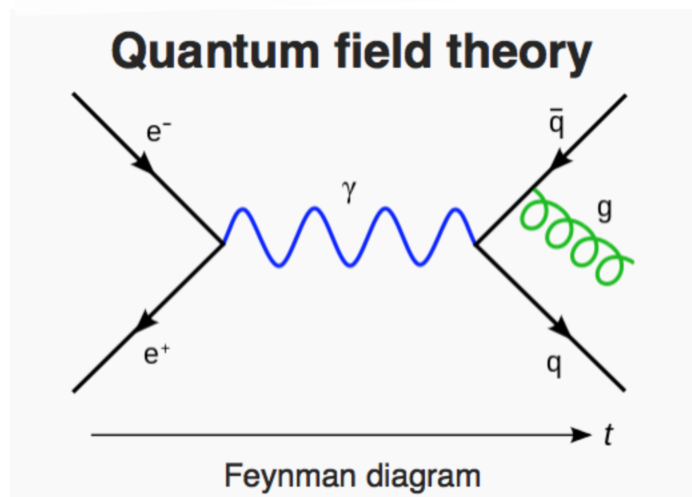
The Fundamental Forces of Nature

Our forces and interactions in particle physics are described by quantum field theories with special symmetry properties, so called gauge theories, which consist of gauge fields, eg the electro-magnetic field.
Symmetries: local gauge invariance (which eg leads to the photon in QED)

The Standard Model can be fully described on a tea-cup (or T-shirt) ☺



	Small →	
Fast ↓	Classical mechanics	Quantum mechanics
	Relativistic mechanics	Quantum field theory



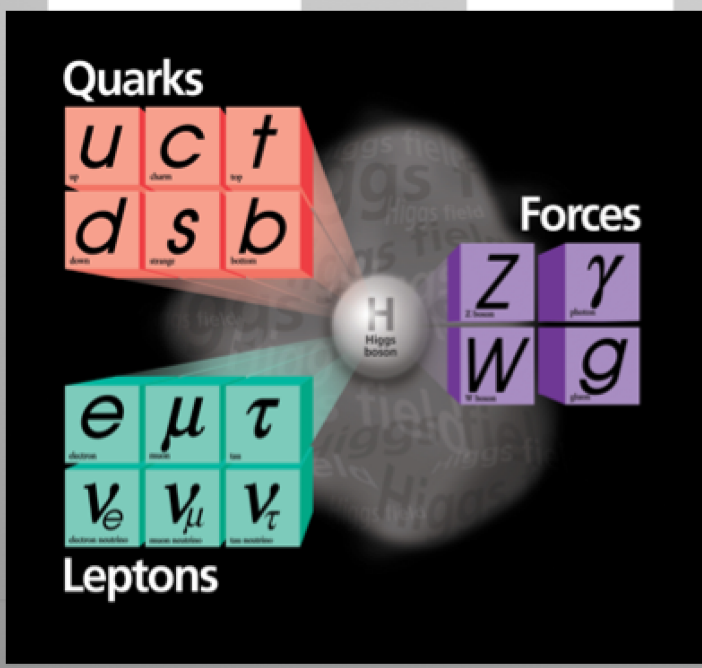
The "Standard Model" of Particle Physics

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) "Periodic Table" of fundamental elements:

Fermions

Bosons

Matter particles



Force particles

The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time
A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!

Fermions: particles with spin ½
Bosons: particles with integer spin

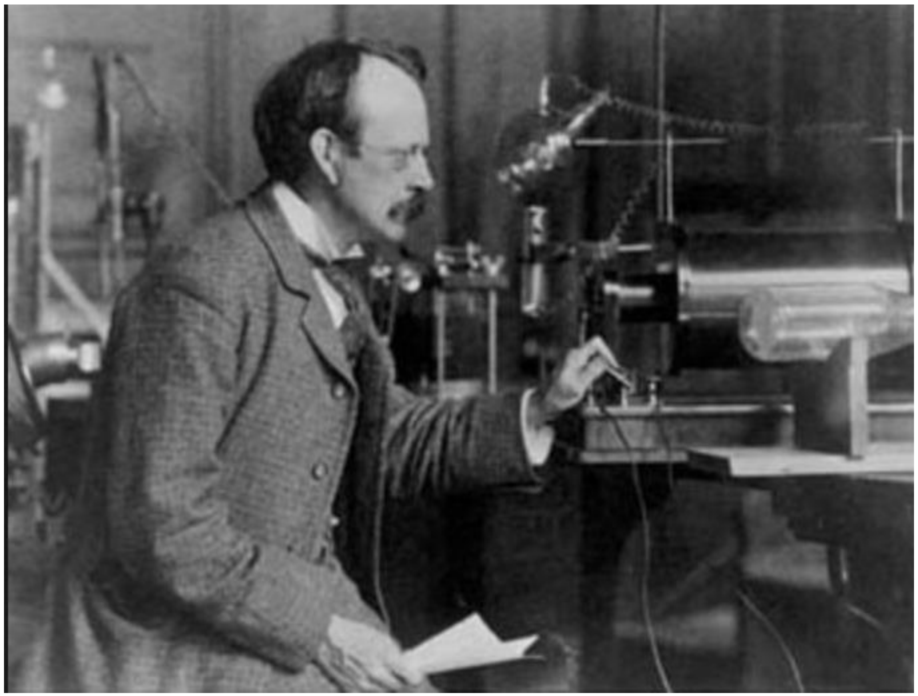
How did we come to
that picture of Nature?

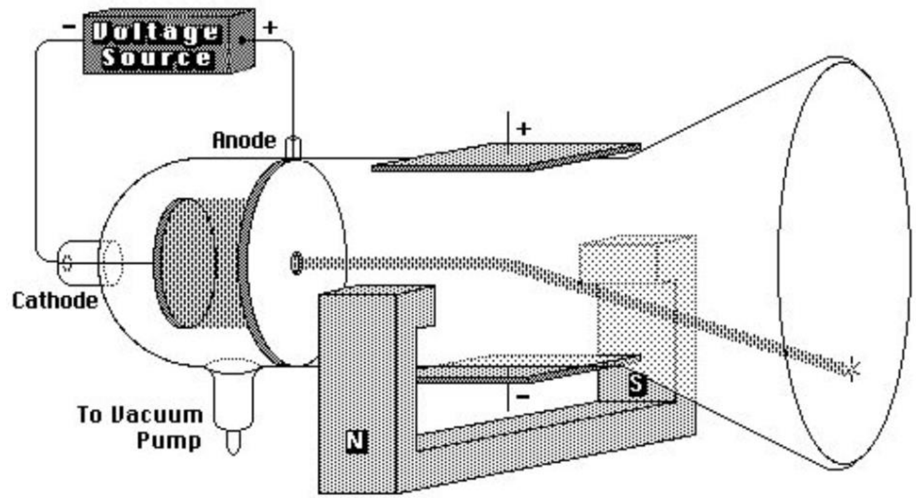
Lets go back to the beginning
of the last century

With some images used from Prof. Fritzsch

The Discovery of Electron

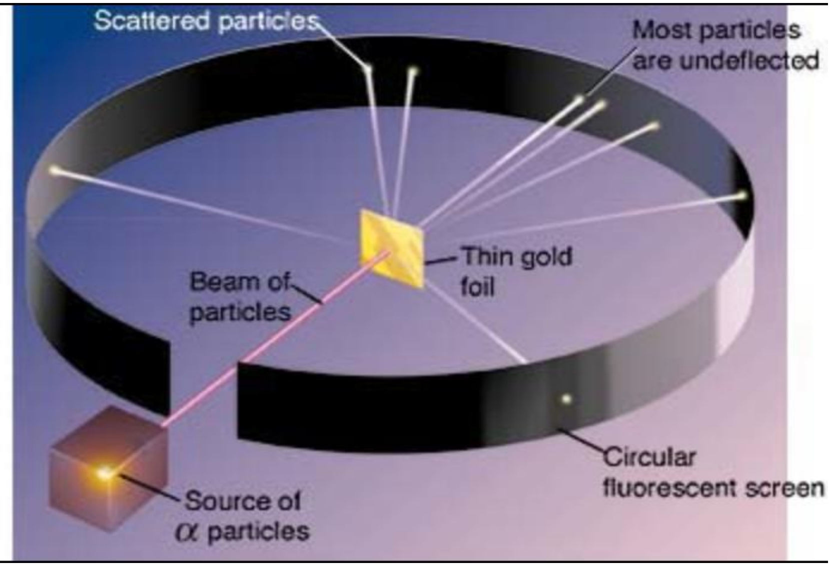
1897: The start of particle physics?
J.J. Thomson discovers the electron, using ‘cathode rays’
The electron is charged, it is deflected by a magnetic field

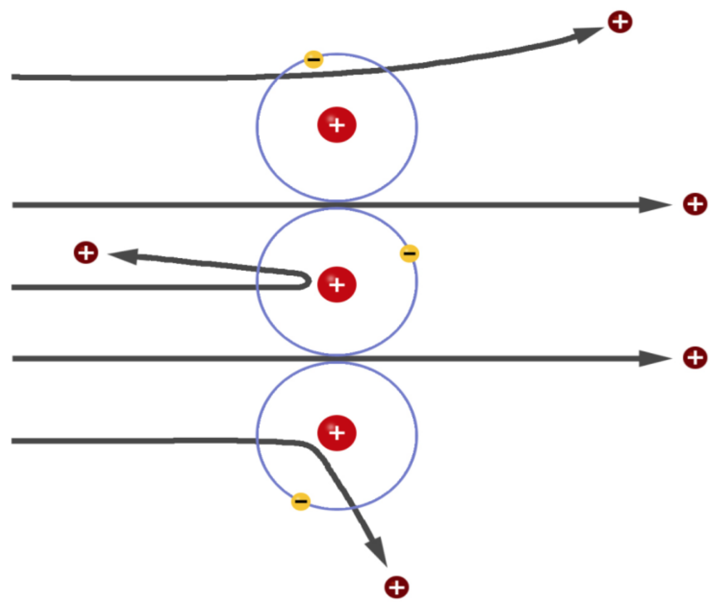




This was also the first “particle accelerator”

Discovery of Nucleus/Proton

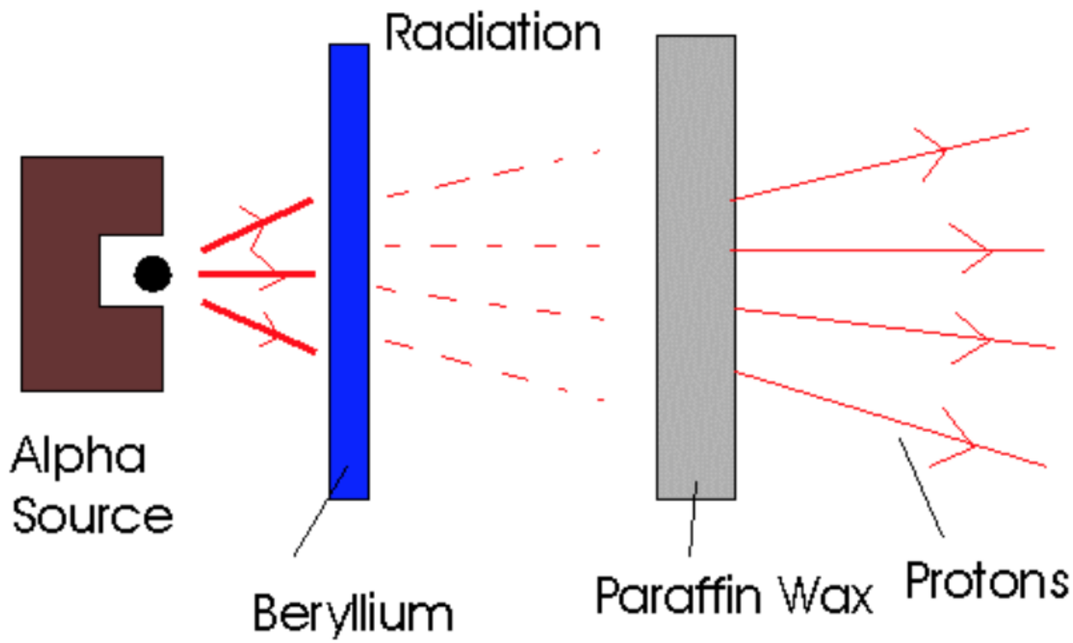




Rutherford experiment:
Unexpected backscattering of α-particles:
Evidence for the structure of atoms !! (1909)
The nucleus of the lightest atom (hydrogen) was named proton

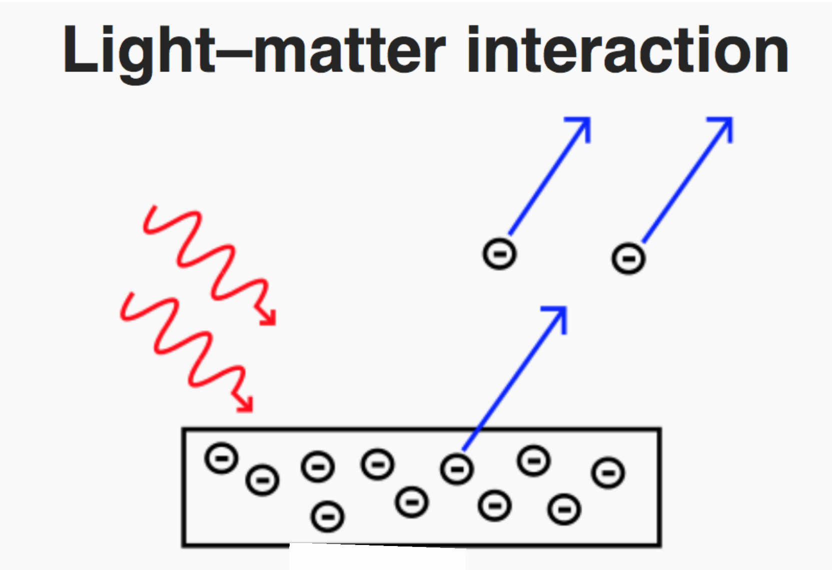
Discovery of Neutron

We knew from the atomic mass spectra that there had to be another particle in the nucleus.
J. Chadwick discovers the neutron in 1932



We now know about the electron, proton and neutron…

Discovery of the Photon

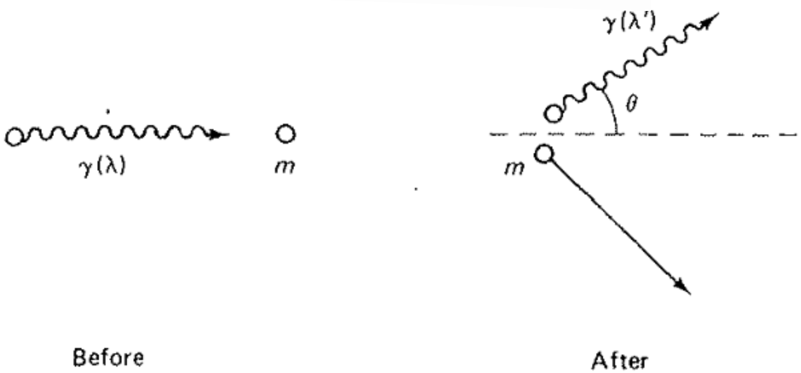


$$E = h\nu$$

$$h = 6.626 \times 10^{-27} \text{ erg s}$$

Particle character of light
(Einstein 1905)

The **photoelectric effect** is the observation that many metals emit electrons when light shines upon them. Electrons emitted in this manner can be called *photoelectrons*. The phenomenon is commonly studied in electronic physics, as well as in fields of chemistry, such as quantum chemistry or electrochemistry.



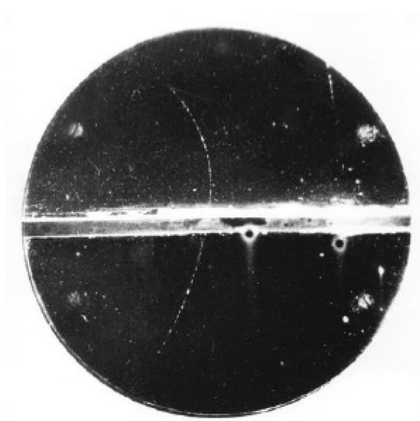
Light scattering of a particle
This settled the particle character of light
(Compton 1923)

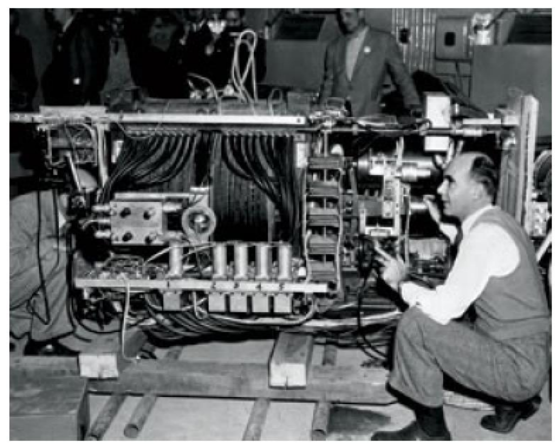
$$\lambda' = \lambda + \lambda_c(1 - \cos\theta)$$

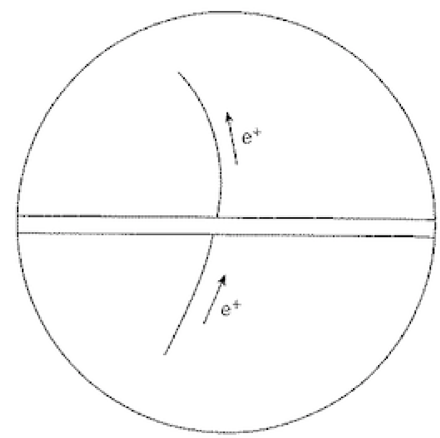
Experiment confirmed the predicted wave length shift of the scattered light

Anti-Matter!

Dirac tried to combine Quantum Mechanics with Special Relativity
To his surprise the equations gave TWO solutions for each particle mass, but two different particles eg with different charge. (1927)
So it predicted that the electron (negative charge) has a identical partner with positive charge.
These "positrons" were observed by Anderson in 1932 in a cloud chamber studying cosmic rays.



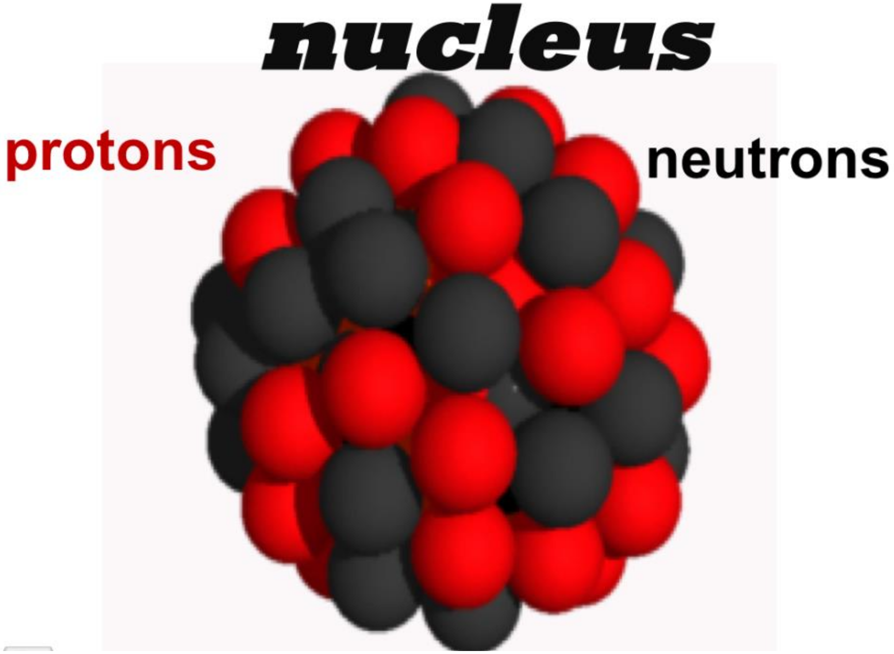


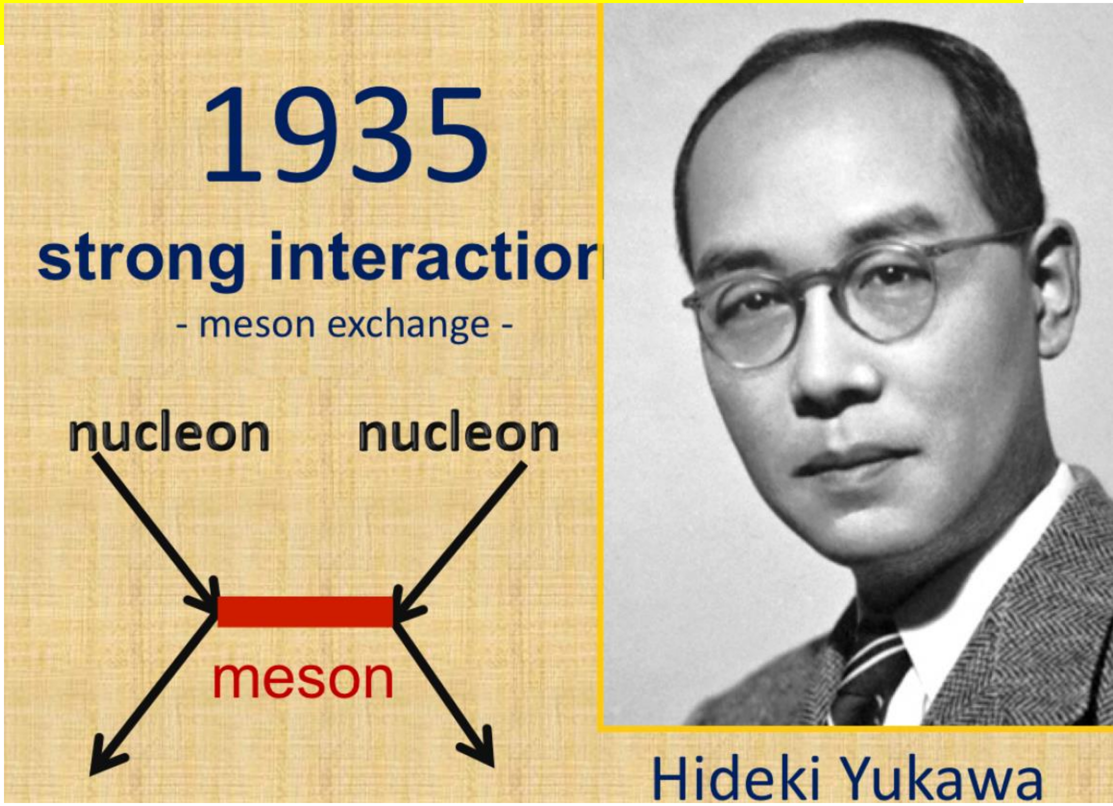


So the number of particles (almost) doubled!

Particle Physics Early 30's

We know of 7 particles . We understand why electrons circulate the atomic nucleus. However what keeps the nucleus together?
We need a new force: the strong force, which is stronger than the electro-magnetic repulsion





H. Yukawa predict a strongly interacting particle with mass $M_{proton}/6$

Cosmic Rays Lead the Field!

Putting detectors for studying cosmic rays, on ground and at high altitudes, led to important discoveries.

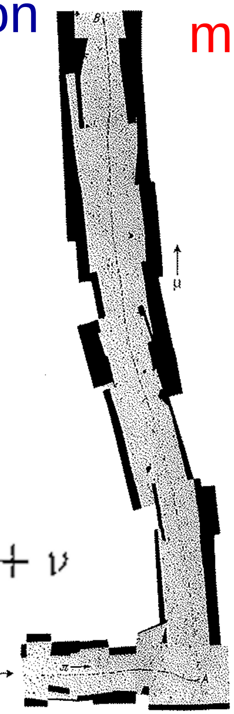
Ground level detectors discovered a particle with a mass of ~ 100 MeV
Was this Yukawa's predicted meson?... No, it did not carry strong force
This particle is now know as the muon (and is family of the electron)

Nuclear emulsion

muon

Higher altitude detectors discovered a particle with a higher mass of ~ 150 MeV that decayed in a muon.
This was a true meson, now called pion (1947)

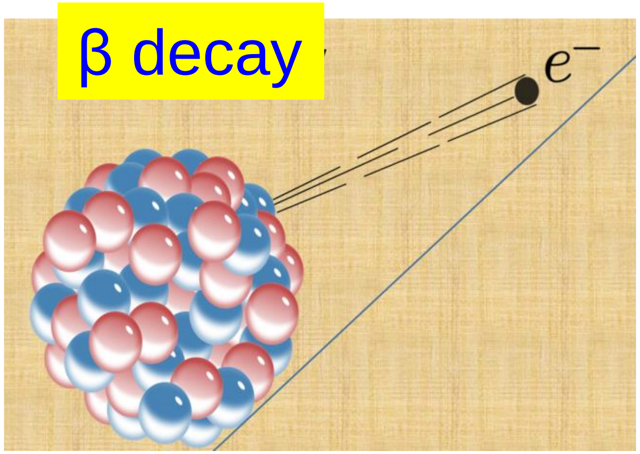
The age of particle physics was truly starting!!
(little did they know at the time)



$\pi \rightarrow \mu + \nu$

meson (pion)

Another New Particle?



If the process is A -> B + electron, the energy of the electron should be at a fixed value. This is not the case! Energy-momentum not conserved in Beta-decays?

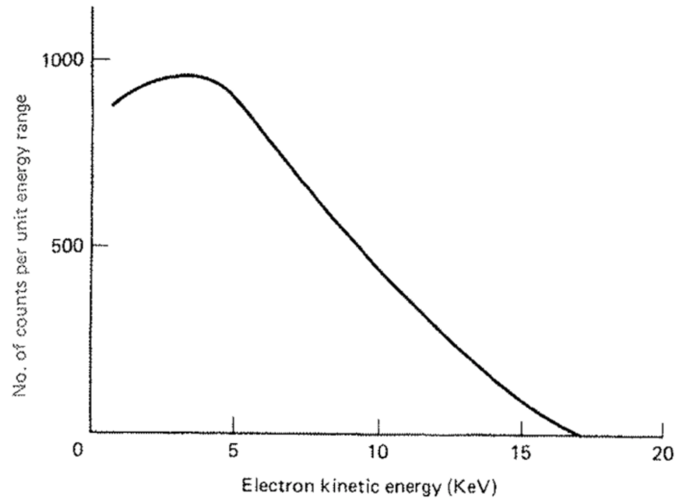


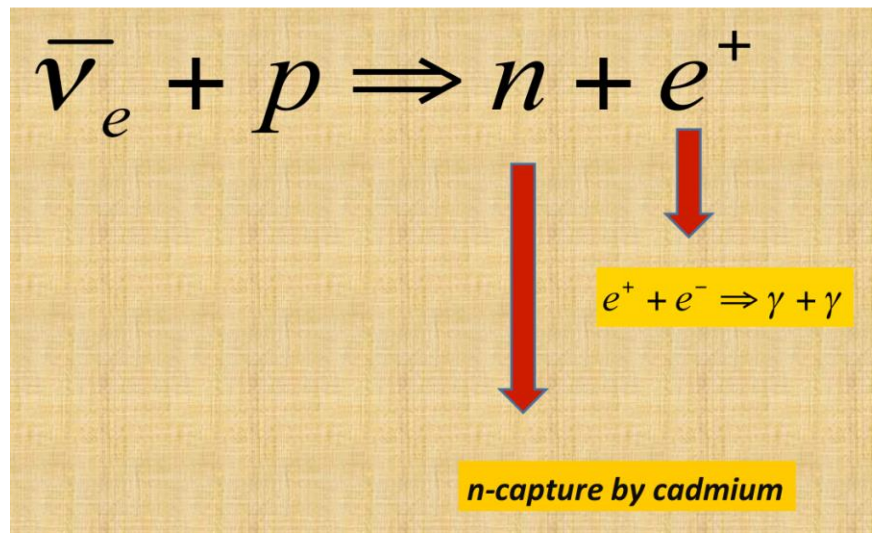
Fig. 1.5 The beta decay spectrum of tritium ($^3_1H \rightarrow ^3_2He$). (*Source*: Lewis, G. M. (1970) *Neutrinos*, Wykeham, London, p. 30.)

Pauli proposed instead the process:

$$n \rightarrow p^+ + e^- + \bar{\nu}$$

The Discovery of the Neutrino

It took 26 years to detect this particle. Cowan and Reines put a water tank close to the reactor in South Carolina and observed the inverse beta decay process (few events/hour)



The neutrino really exists!

Particle Terminology

Leptons -> light particles: electron, muon, neutrinos

Mesons -> medium mass particles: pions

Baryons -> heavy particles: protons, neutrons

Experimentally one established the

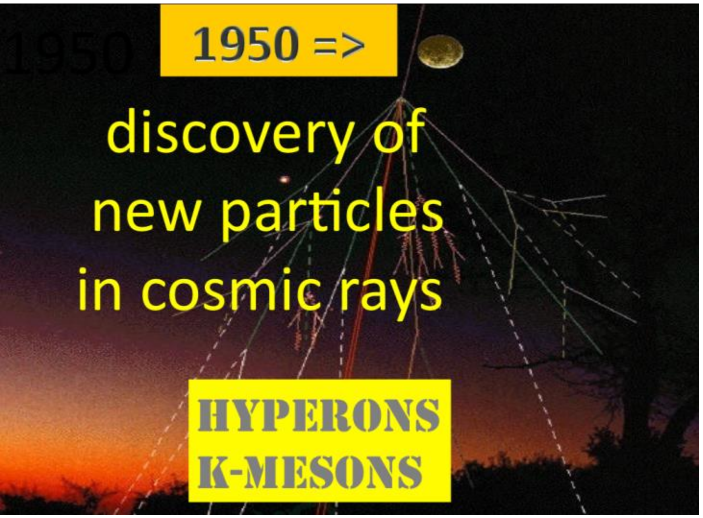
- Conservation of lepton number in collisions
- Conservation of baryon number in collisions

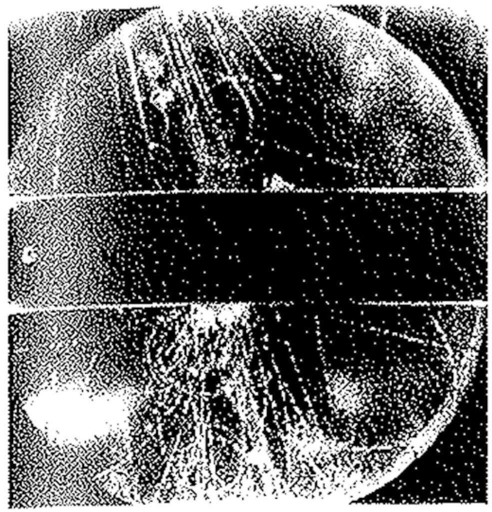
There are however at this point no theoretical symmetries that impose these conservation laws

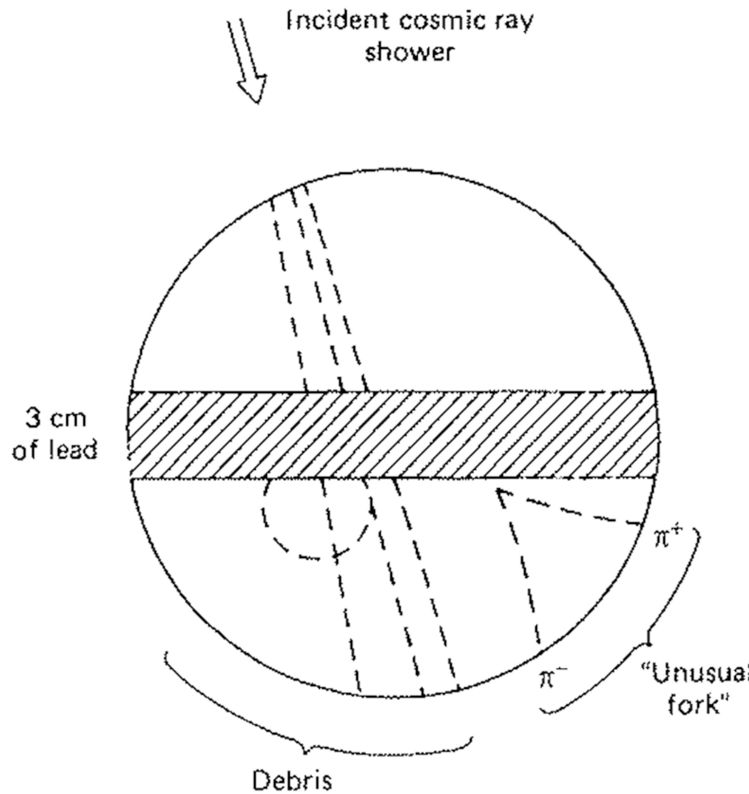
1947: So it looks that we have all the particles we need, right?

But scientist continued to look…

First Surprise: a new ‘strange’ particle







$$K^0 \rightarrow \pi^+ + \pi^-$$

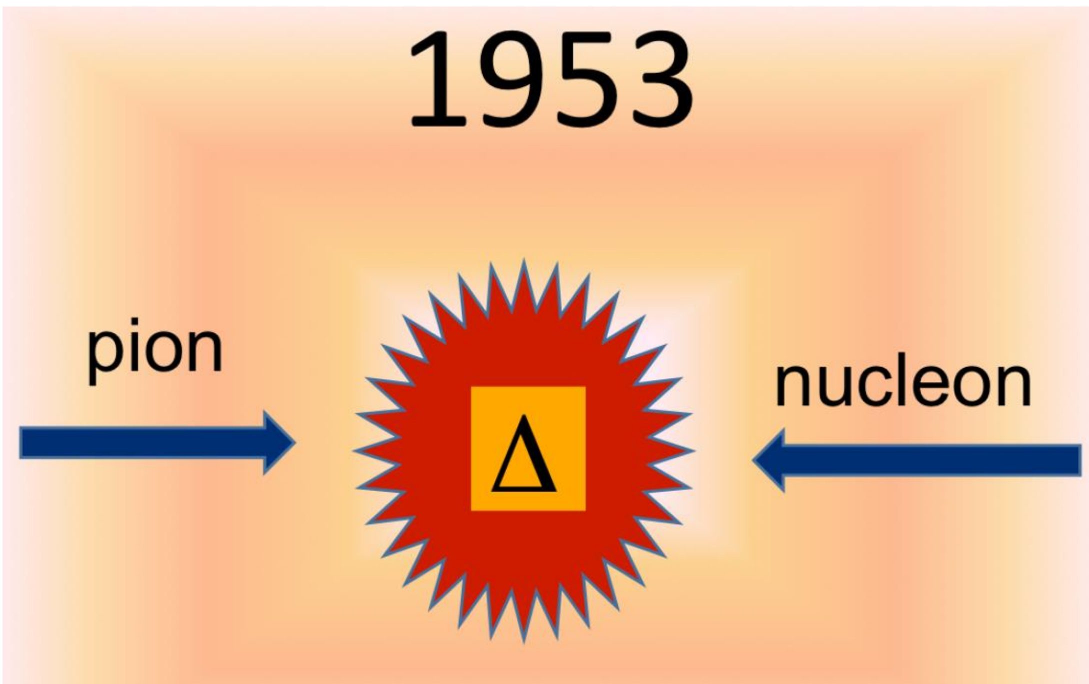
$$K^+ \rightarrow \pi^+ + \pi^+ + \pi^-$$

These new mesons (and later the corresponding baryons) showed strange decays, hence the new quantum number “strangeness” was introduced
Particle can have strangeness 0, +1, -1, +2, -2, +3, -3

More Particles: Baryon Resonances

In the 1950's the first particle accelerators were put in to use, eg at LBL, Berkeley, California

An example observed in the scattering of protons and pions



Particles with Strangeness

$$\pi^- + p^+ \rightarrow K^+ + \Sigma^-$$
$$\rightarrow K^0 + \Sigma^0$$
$$\rightarrow K^0 + \Lambda$$

$$\pi^- + p^+ \not\rightarrow \pi^+ + \Sigma^-$$
$$\not\rightarrow \pi^0 + \Lambda$$
$$\not\rightarrow K^0 + n$$

Strangeness is produced in pairs (conserved) in production
Strangeness is NOT conserved in decays

$$\Lambda \rightarrow p^+ + \pi^-$$
$$\Sigma^+ \rightarrow p^+ + \pi^0$$
$$\rightarrow n + \pi^+$$

Particles have an unusual long decay time (10^{-13} sec) compared to particles decaying via strong interactions such as the Δ Baryon (10^{-23} sec)
-> decay is via the weak interaction

A New Paradigm ? ☺

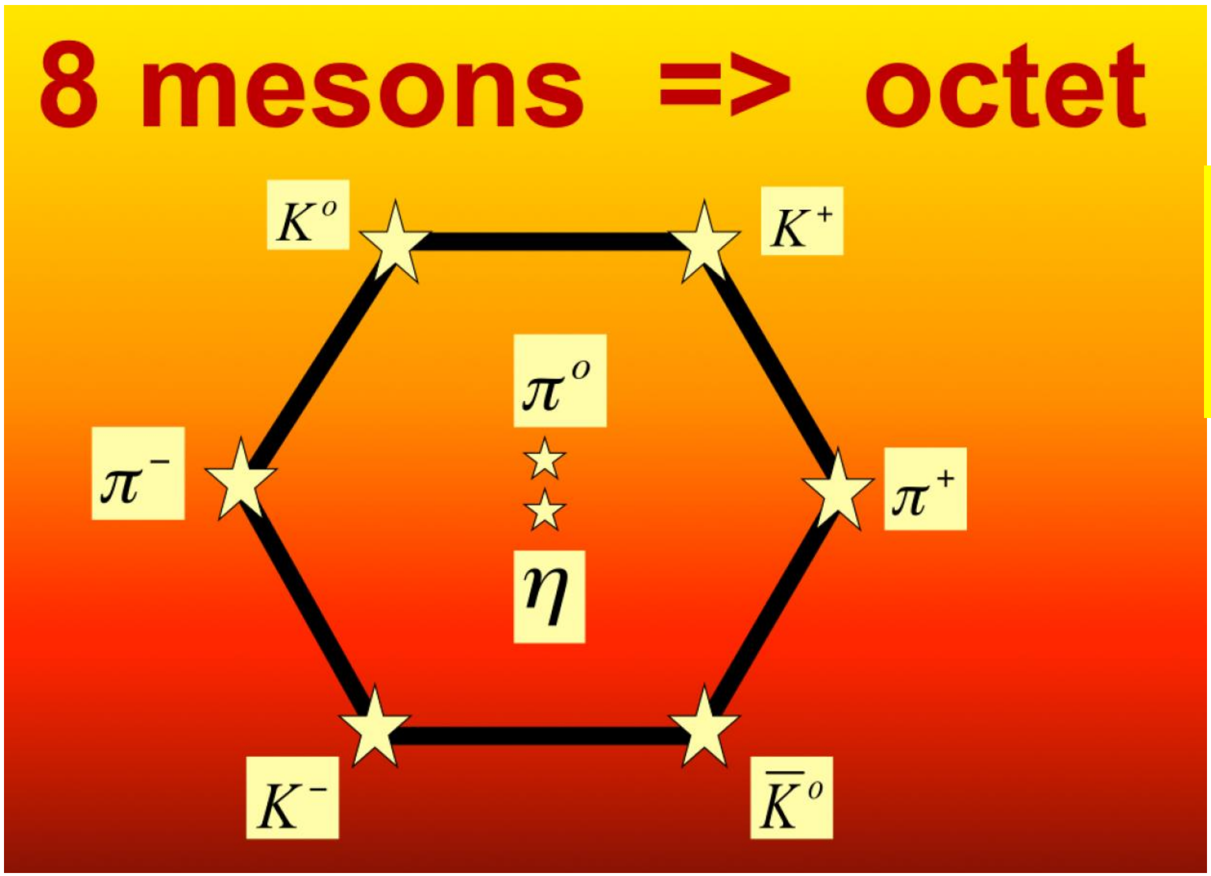
Willis Lamb (in his Nobel Prize acceptance speech)

1955

When the Nobel Prizes were first awarded in 1901, physicists knew something of just two objects which are now called "elementary particles": the electron and the proton. A deluge of other "elementary" particles appeared after 1930; neutron, neutrino, μ meson (sic), π meson, heavier mesons, and various hyperons. I have heard it said that "the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine".

1961: Classification of all Particles

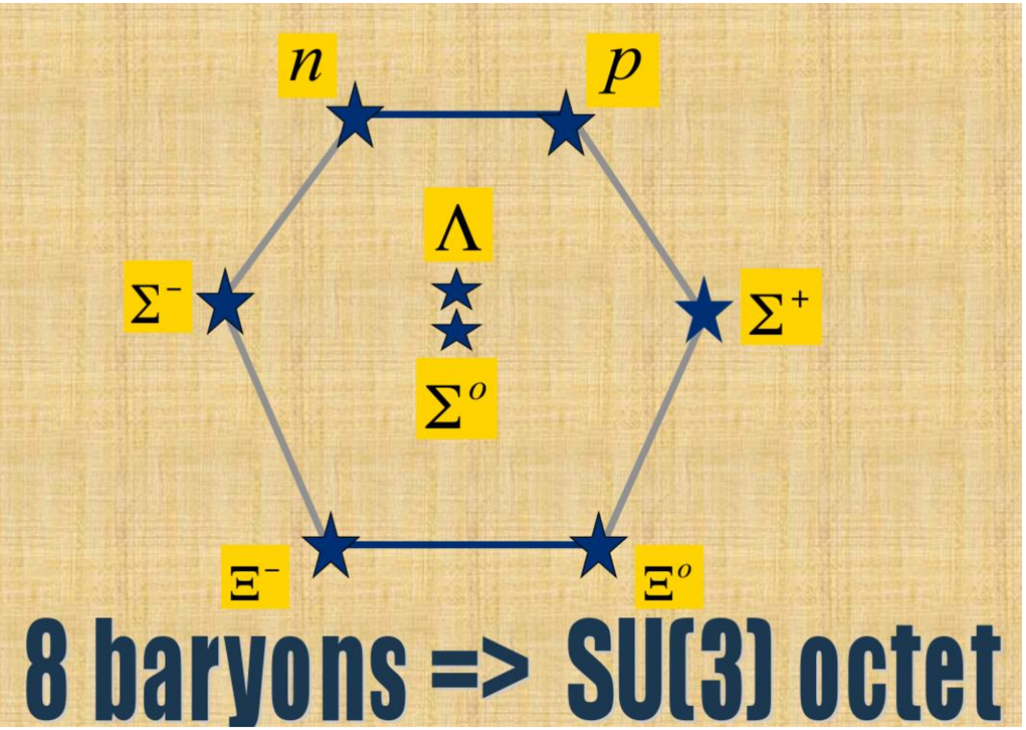
Several 10's of particles discovered by then. Is there an underlying structure like eg for the periodic table of the chemical elements? Proposal from Gell-Mann (and Ne'eman) in 1961, based on SU(3) symmetry group: The Eightfold Way

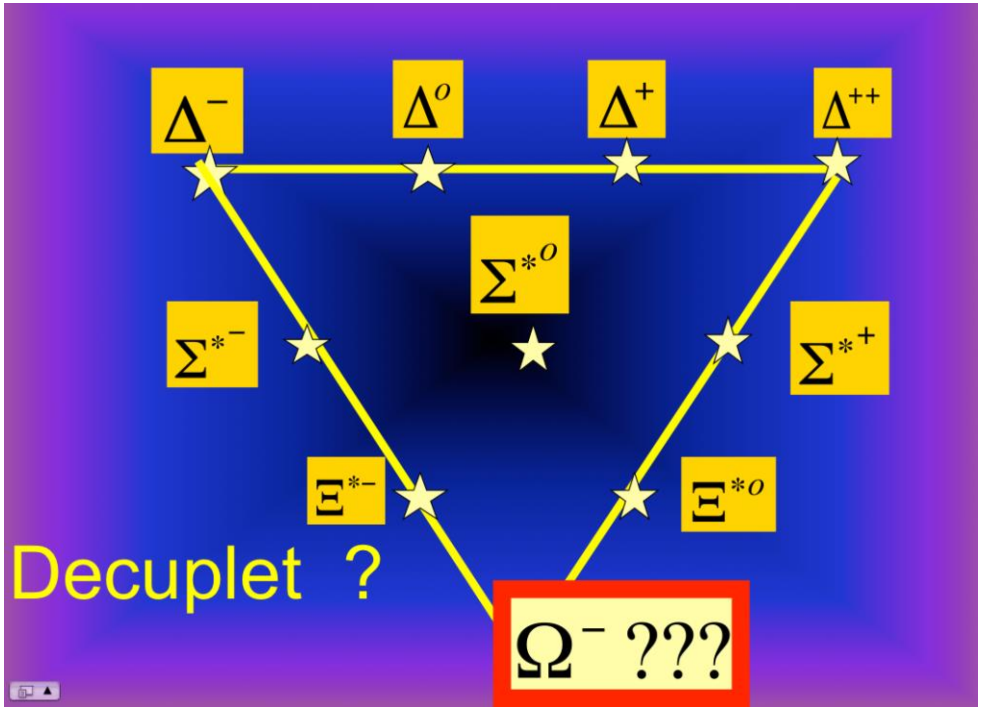


All mesons fit in "octets" like this one (lowest energy mesons)

1961: Classification of all Particles

Baryons fit in octet and decuplet representations of SU(3)
Special Unitary (Lie) Group of degree 3 with 3x3 matrices





Except… there seems to be a particle missing…
Gell-man made a prediction for the mass of this missing particle

1961: Classification of all Particles

…and it was found in 1964 at the Brookhaven accelerator

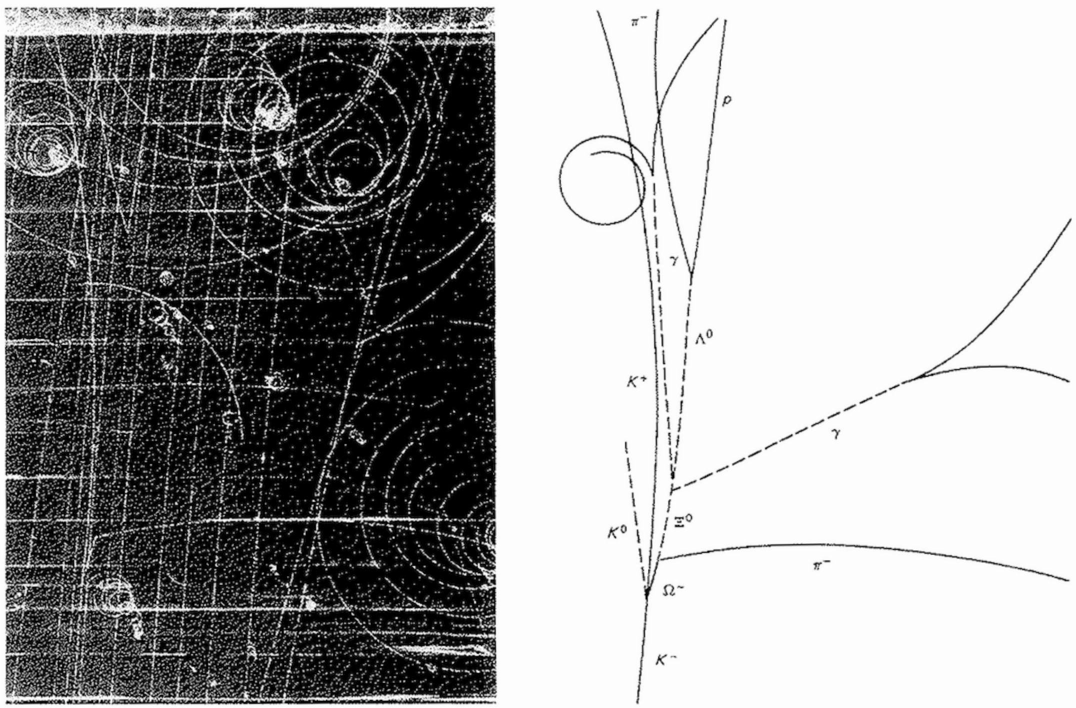
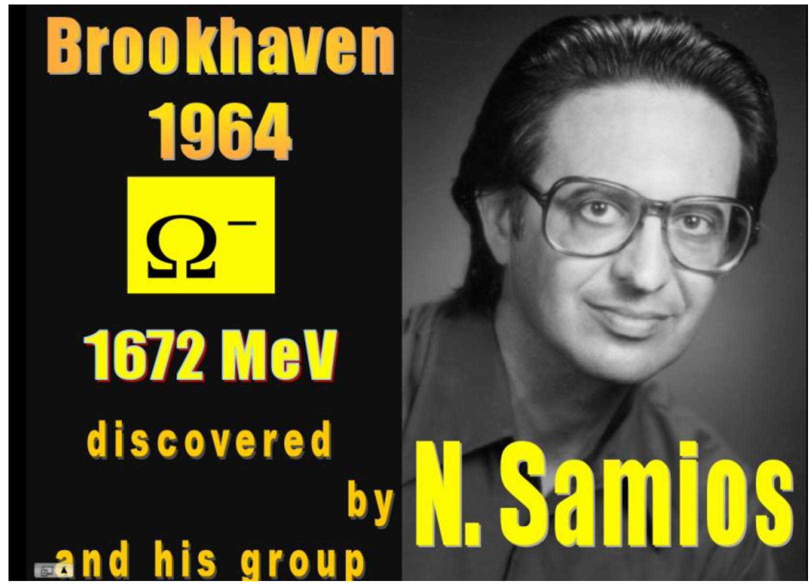


Fig. 1.9 The discovery of the Ω^-. The actual bubble chamber photograph is shown on the left; a line diagram of the relevant tracks is on the right. (Photo courtesy Brookhaven National Laboratory.)

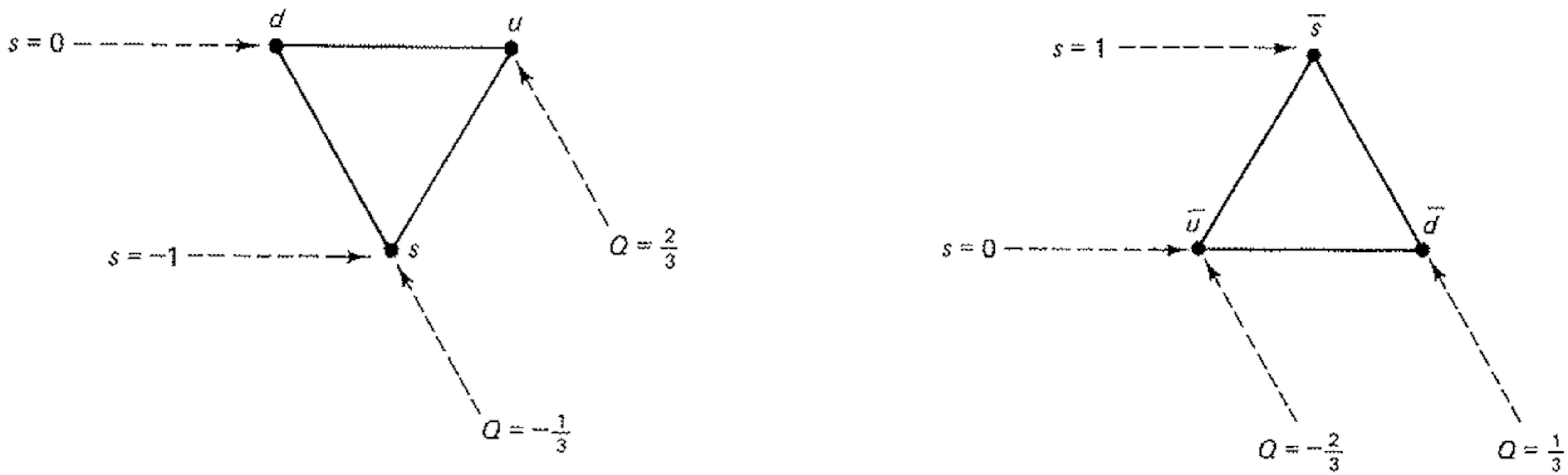


But what does this all mean???

1964: The Quark Model

As in chemistry: the pattern suggests an underlying substructure!
•Gell-mann -> quarks (from “Finnegans Wake” from J. Joyce)
•Zweig -> aces (idea only published as a CERN preprint)
Quarks became the accepted word. Quarks come in flavors…

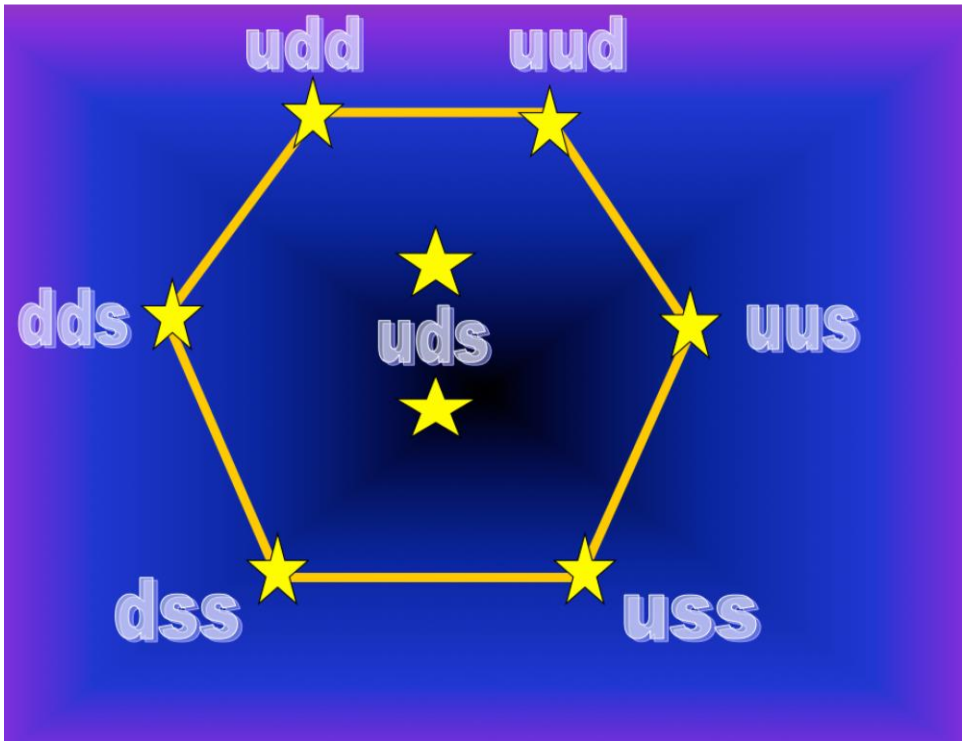
The fundamental quark and anti-quark SU(3) triplets

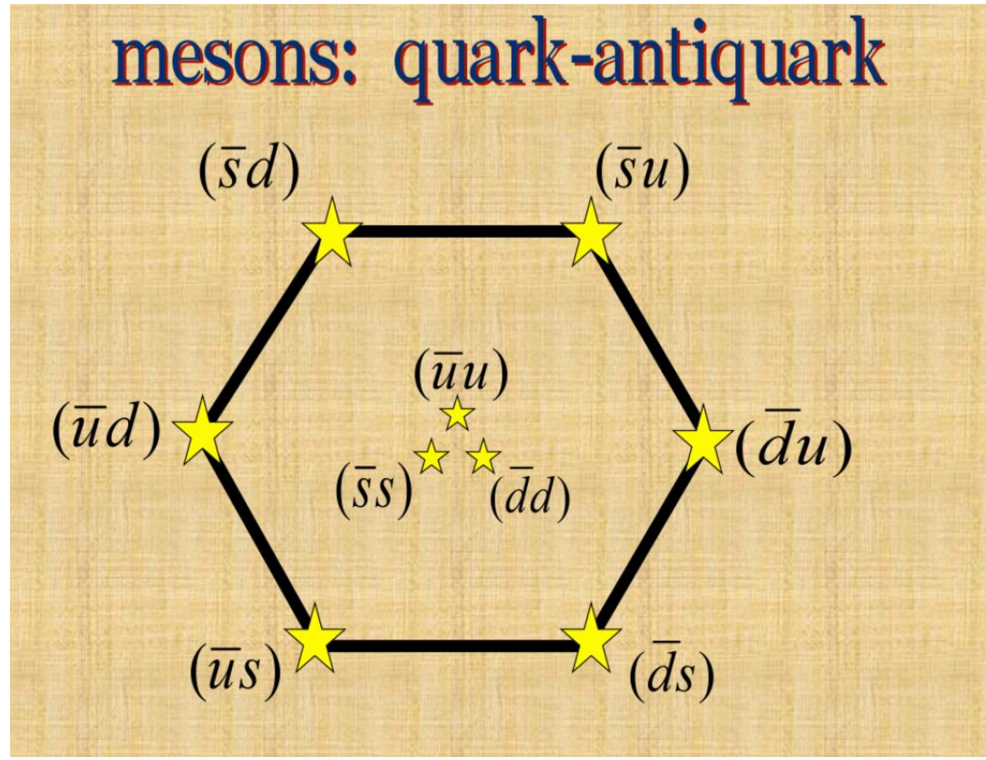


Originally: 3 quark flavors u (up), d (down) and s (strangeness)

1964: The Quark Model

- Baryons would consist of 3 quarks
- Mesons consist of a quark and an anti-quark





Quark Properties

electric charges

$u: \ {}^{2}\!/_{3}\, e$

$d: \ -{}^{1}\!/_{3}\, e$

$s: \ -{}^{1}\!/_{3}\, e$

m(u): 5 MeV
m(d): 7 MeV
m(s): 110 MeV

→ SU(3) broken

Quarks should have fraction charges
Quarks (u,d,s) are sort of light particles

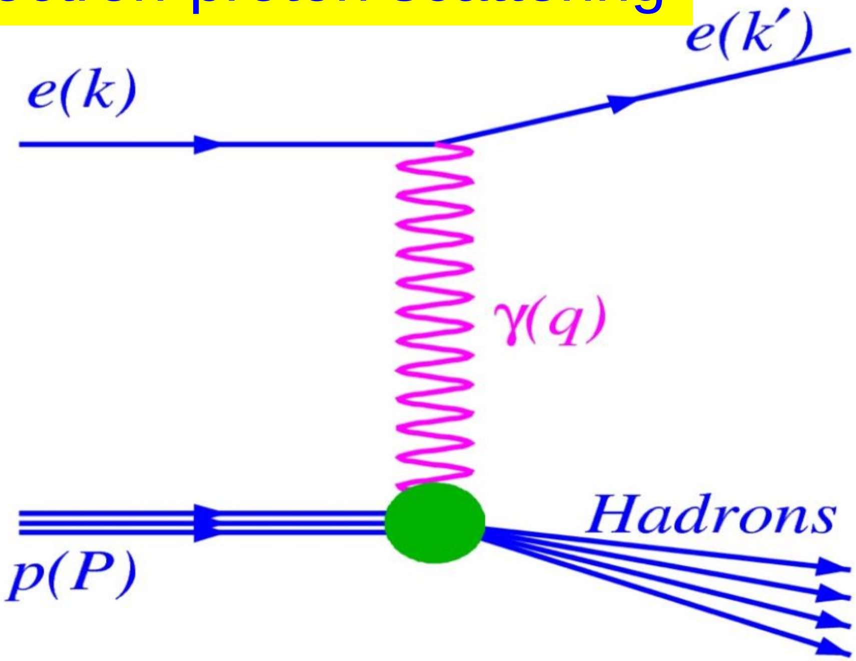
Note m(d) > m(u) -> mass neutron (udd) > mass proton (uud)

But are quarks real or just a mathematical trick?

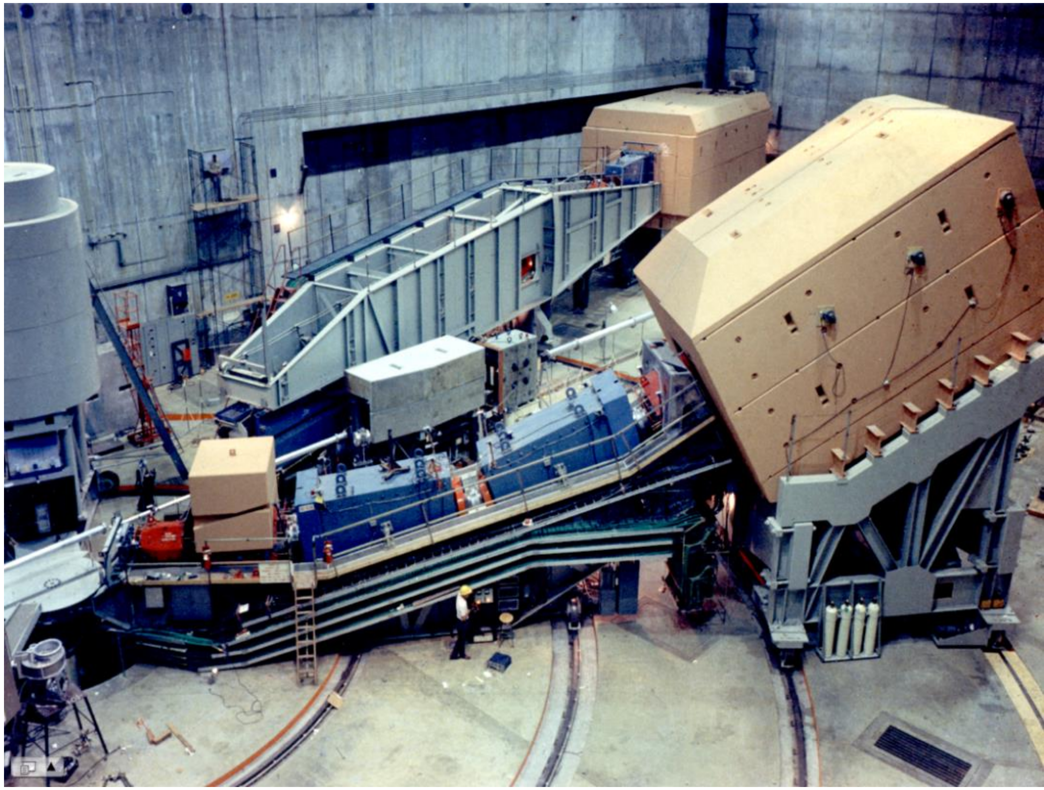
The Search for Proton Substructure

Problem: we did not observe any free quarks, even at higher energies.
Design experiment to probe quark charge: electron-proton scattering

Electron-proton scattering



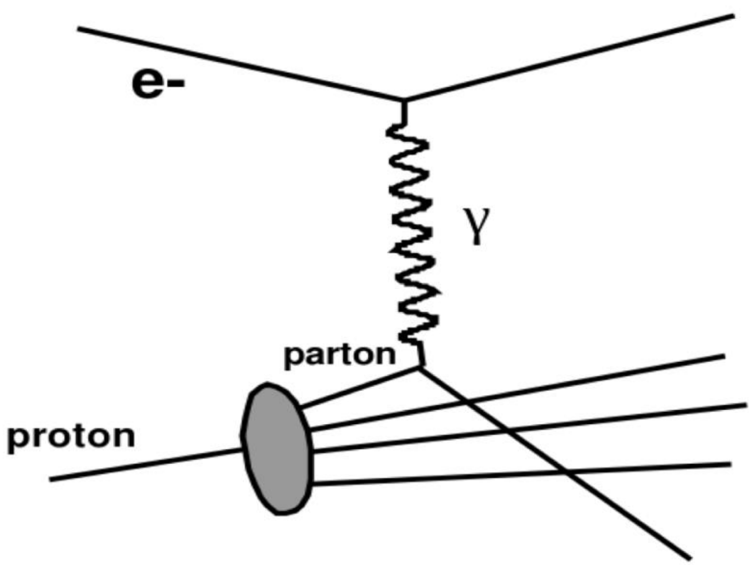
This process is called
Deep Inelastic Scattering (DIS)

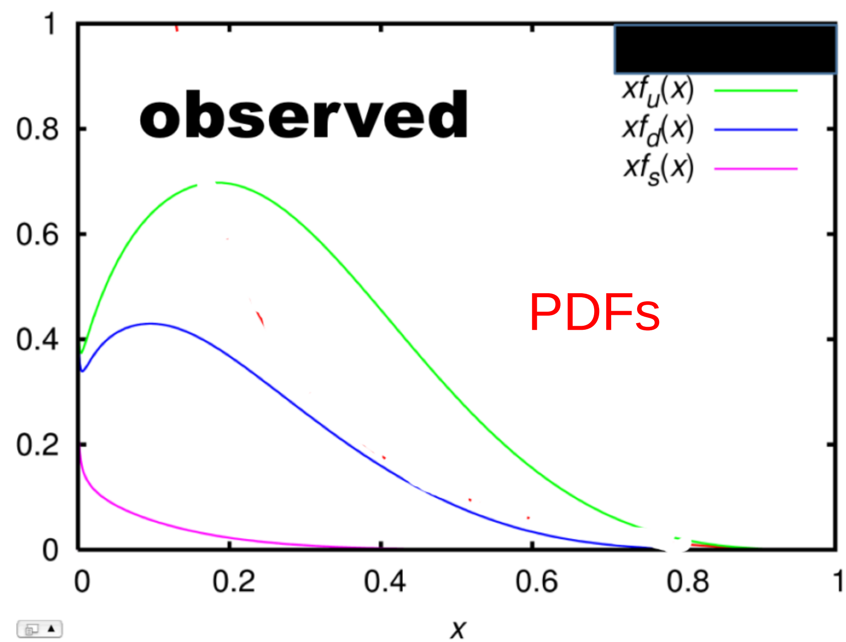


SLAC end station-A experiment

The Search for Proton Substructure

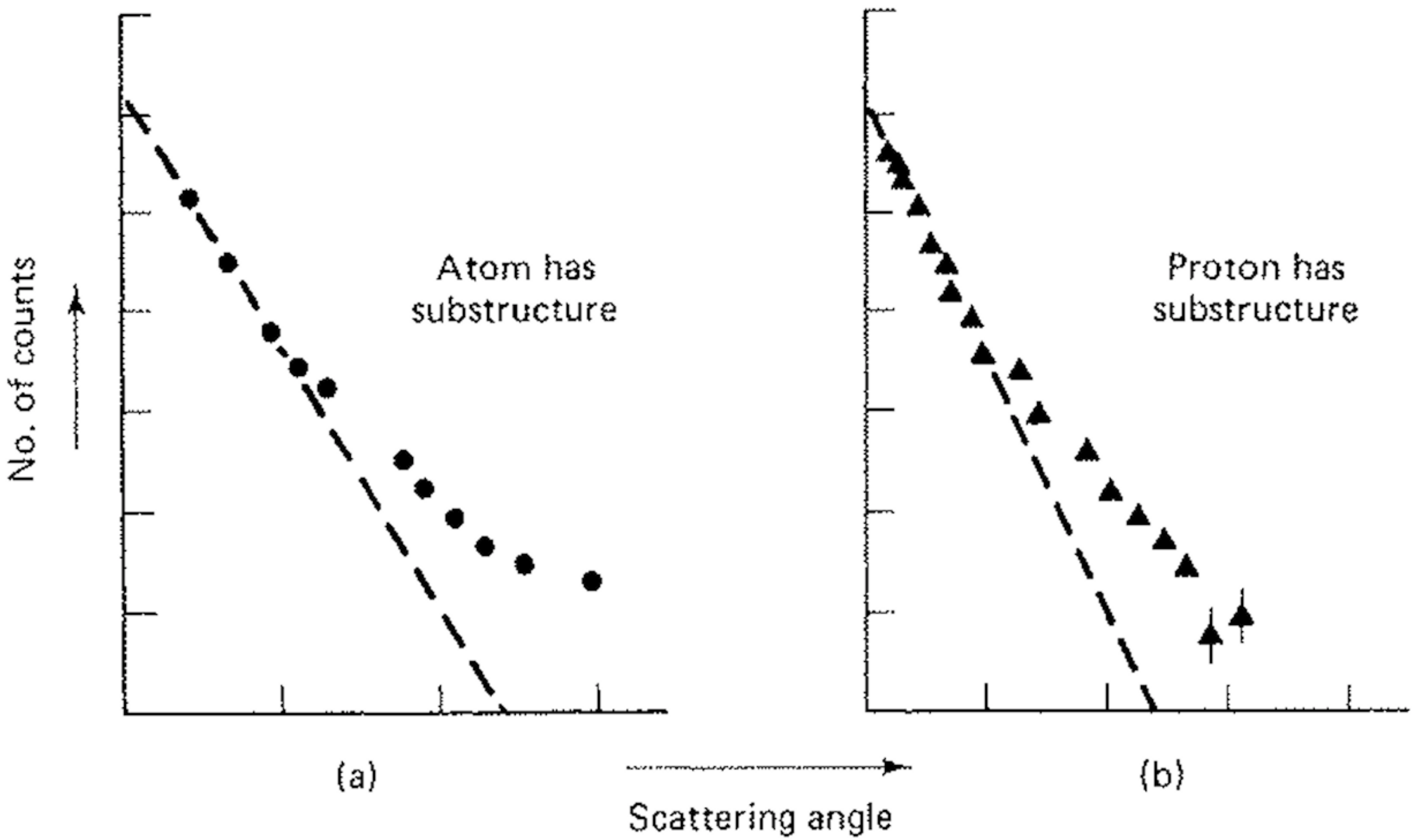
The Electron-Proton experiment observed a 'lumpy' structure in the protons, consistent with 3 'partons' ie smaller substructure particles and fractional charge. The distribution of the fractional momentum of these partons ($x = p_{parton}/p_{proton}$) is a continuous distribution, now called parton density distribution (PDF)





The substructure partons were subsequently identified with the quarks

Further Evidence for Substructure



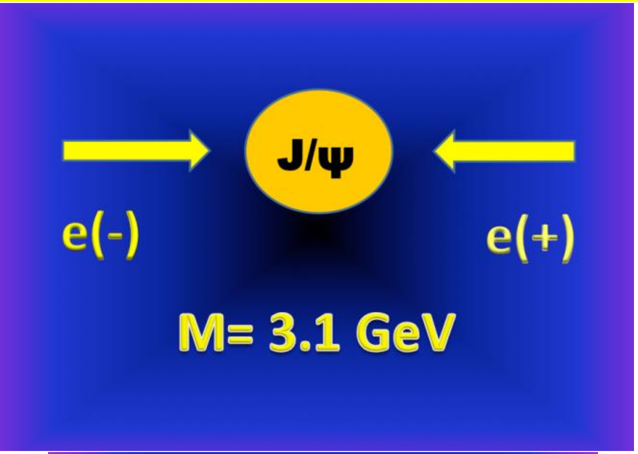
Remember the Rutherford experiment of 1911 !

We measure the angle of scattered particles in proton-proton collisions

Large angle scattering observed! Substructure

The 1974 November Revolution

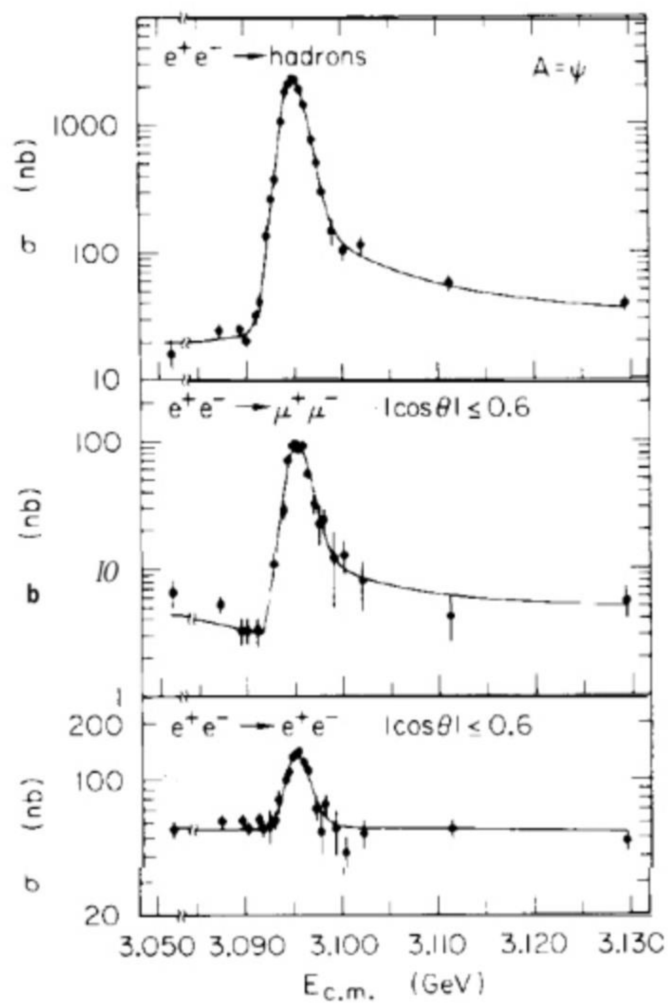
A narrow resonance was simultaneously observed in pp (Brookhaven) and e+e- (SLAC) collisions, with a lifetime of 10^{-20} sec

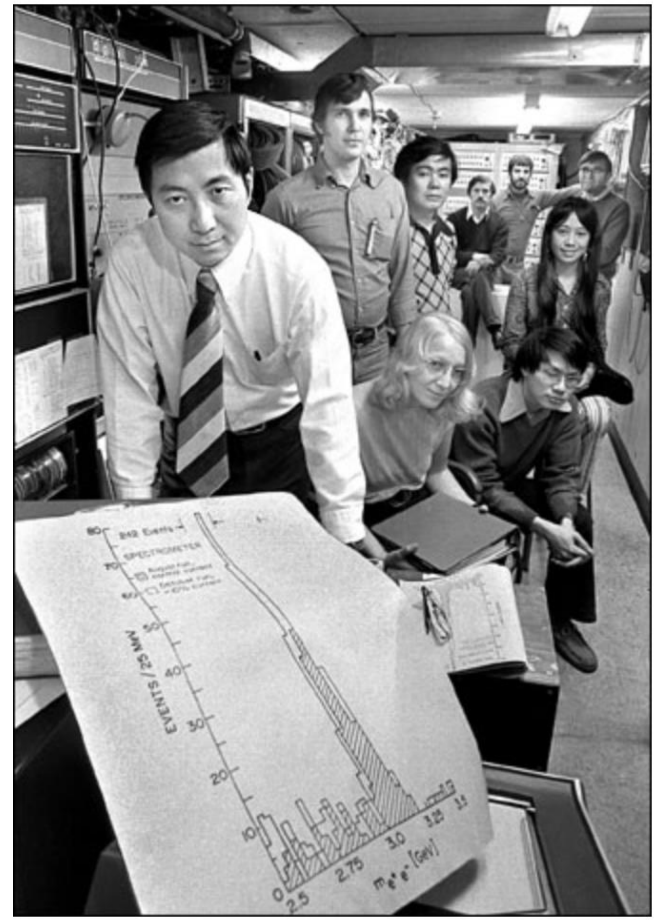


$$J/\psi \Rightarrow (\bar{c}c)$$

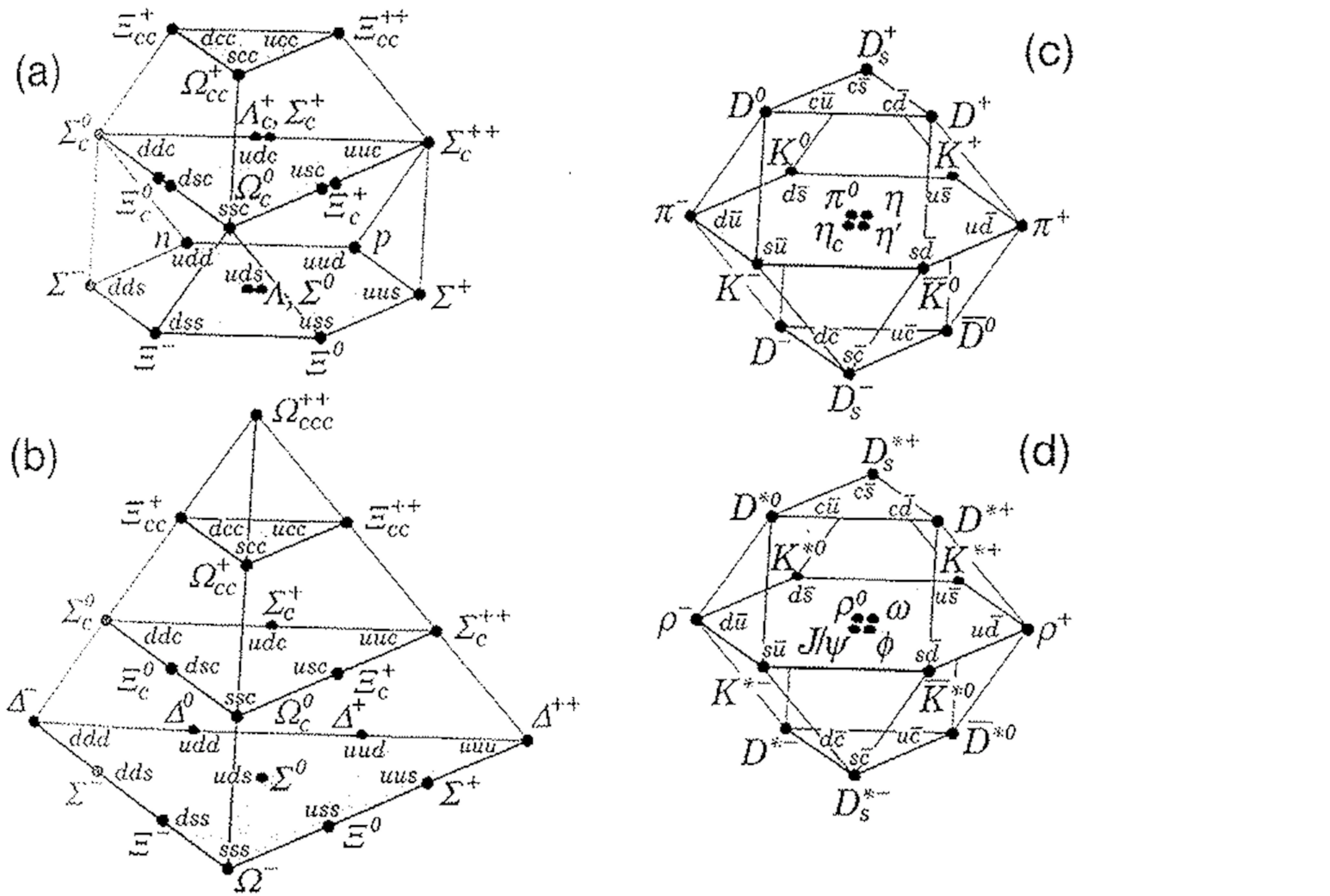
$$c: \quad charm - quark$$

This new particle J/psi particle consists of a new (anti)quark flavor called ‘Charm quark’



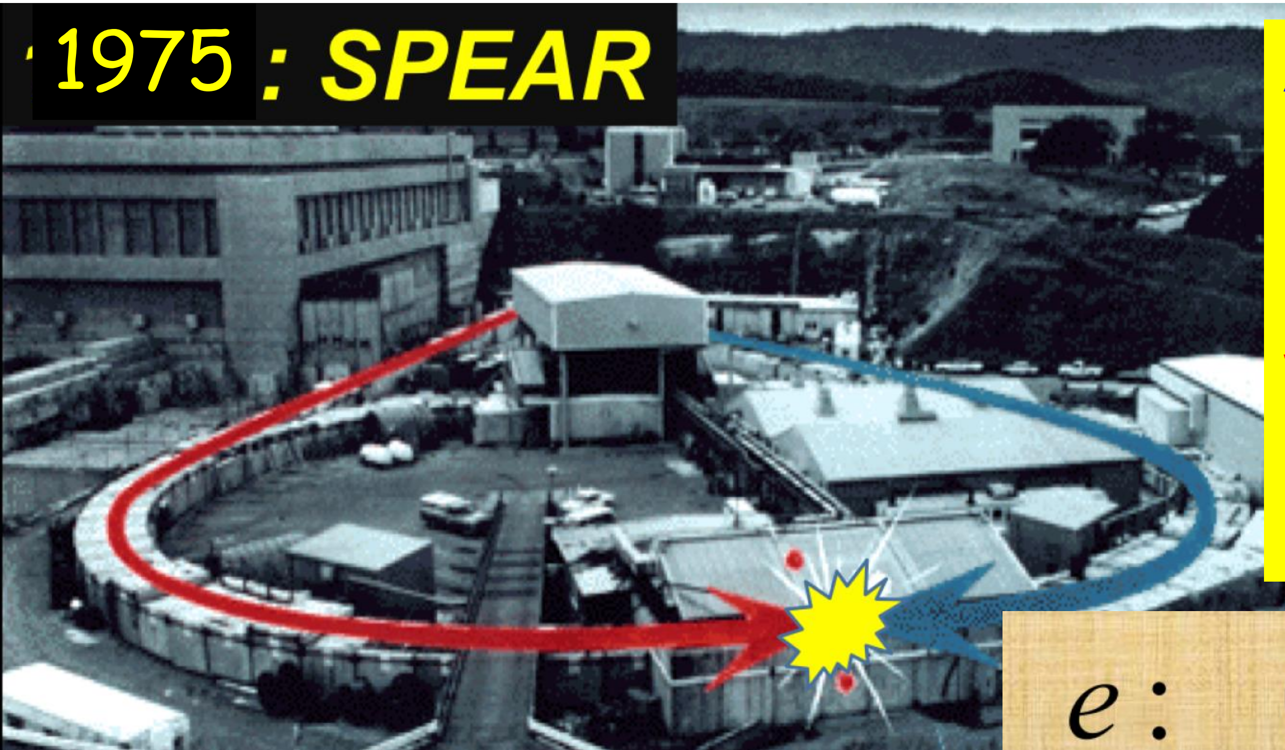


Adding the Charm Quark



The multiplets extended (SU(4)) with baryons and mesons with charm

1975: More Particles Being Discovered



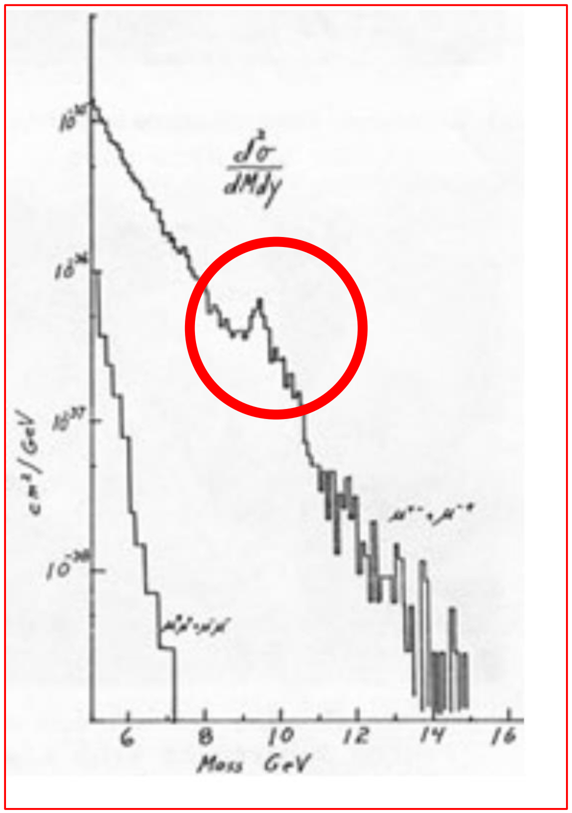
A new heavy lepton was discovered in e+e- collisions at Spear (SLAC)

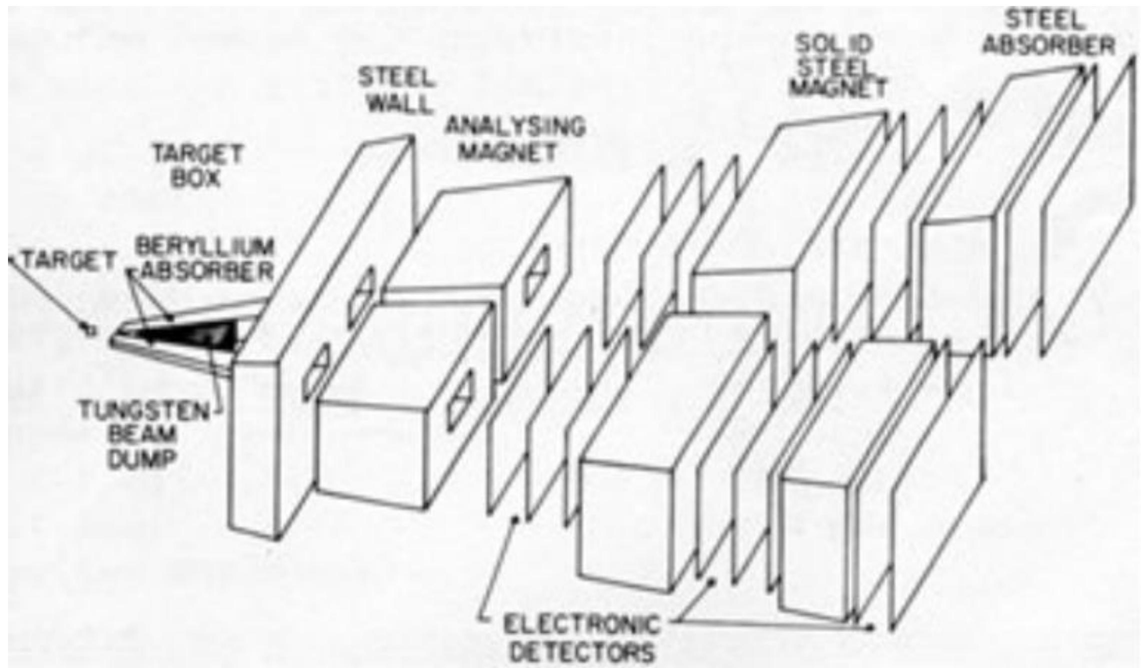
We call this now the tau lepton. It is heavier than the proton

$e:$	0.511	MeV
$\mu:$	105.7	MeV
$\tau:$	1777	MeV

Are there any more Quarks?

1977 Fermilab Chicago: a bump was seen in the di-muon spectrum produced in proton-proton collisions, around 10 GeV. This particle became the “upsilon” and was a bound state of a new quark-antiquark flavor called “b” for ‘bottom’ or ‘beauty’





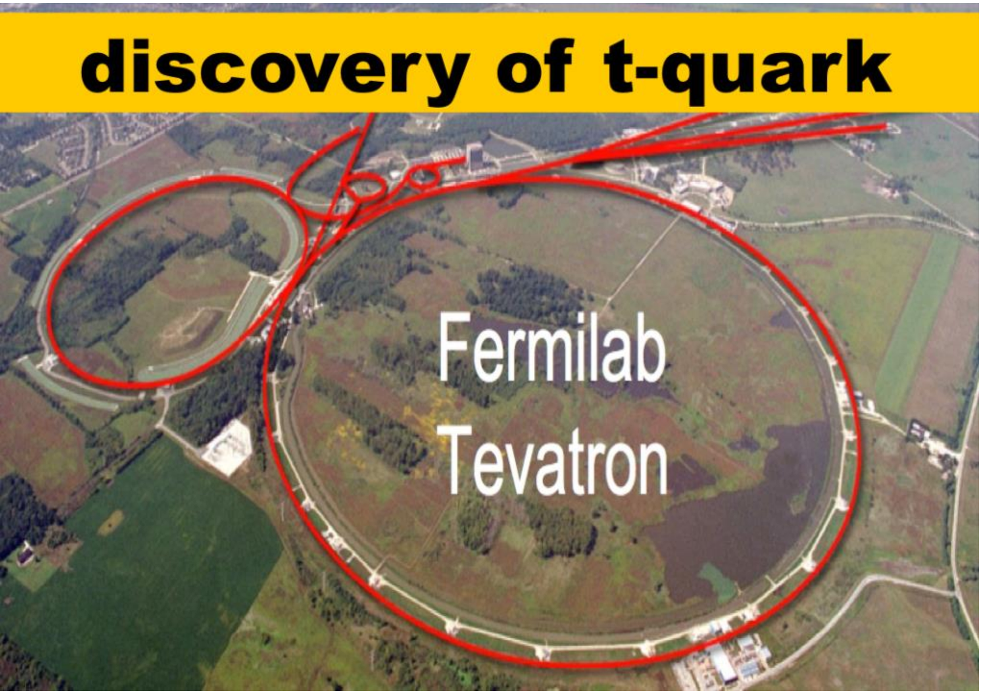
Situation end of the 80's

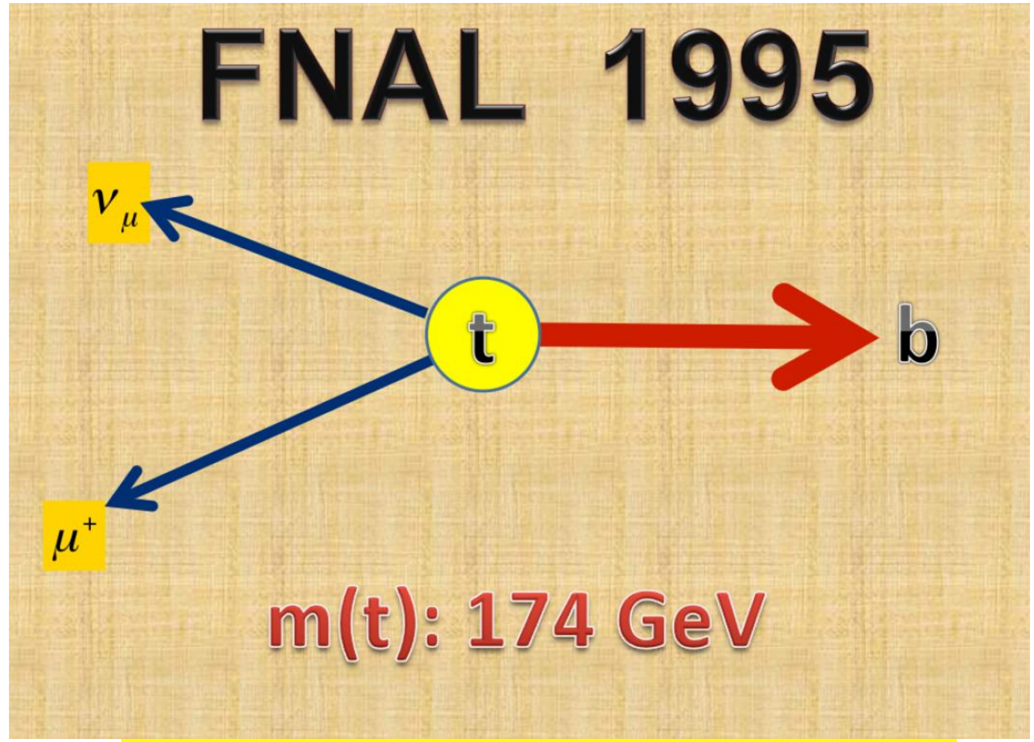
At this point we have 5 quarks…
So now everybody believes a new quark will show up soon!!
It had a name LONG before it was found: the top quark

$$\Rightarrow \begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} ? \\ b \end{pmatrix}$$

The Hunt for the Top Quark

It took however till 1995!!





$$m(t) \approx 174 \quad GeV$$
$$m(b) \approx 4{,}4 \quad GeV$$

The main reason is that this new quark is very heavy… As heavy as a gold nucleus

The Fundamental Particles Table

Quark classification

	q	Q	D	U	S	C	B	T
First generation	d	−1/3	−1	0	0	0	0	0
	u	2/3	0	1	0	0	0	0
Second generation	s	−1/3	0	0	−1	0	0	0
	c	2/3	0	0	0	1	0	0
Third generation	b	−1/3	0	0	0	0	−1	0
	t	2/3	0	0	0	0	0	1

Lepton classification

	l	Q	L_e	L_μ	L_τ
First generation	e	−1	1	0	0
	ν_e	0	1	0	0
Second generation	μ	−1	0	1	0
	ν_μ	0	0	1	0
Third generation	τ	−1	0	0	1
	ν_τ	0	0	0	1

We have 3 generations for both the leptons and quarks

There are 3 neutrino flavors

Is this the end or can there be more –heavier- generations?
This is a priori not excluded the LHC will look for them

Elementary Particle Dynamics

Elementary Particle Dynamics

As far as we know there are four fundamental forces in Nature

Interaction	Strength	Range (m)	Mediator	Mass (GeV)
strong	1	10^{-15}	gluons (8)	0
electromagnetic	10^{-2}	∞	photon	0
weak	10^{-5}	10^{-18}	$W^+ W^- Z^0$	80, 80, 91
gravitation	10^{-38}	∞	graviton	0

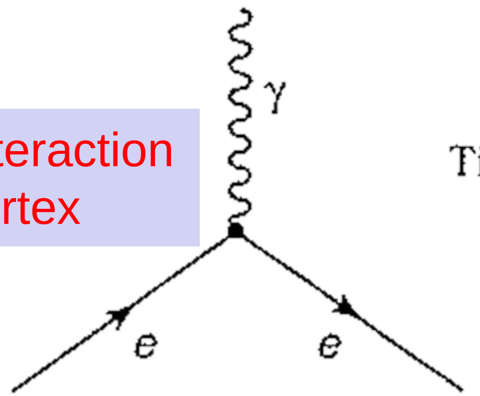
The forces are described by quantum field (gauge) theories with local gauge invariace (theory lectures)
The action in the theory is exchanged by a mediator/messenger.

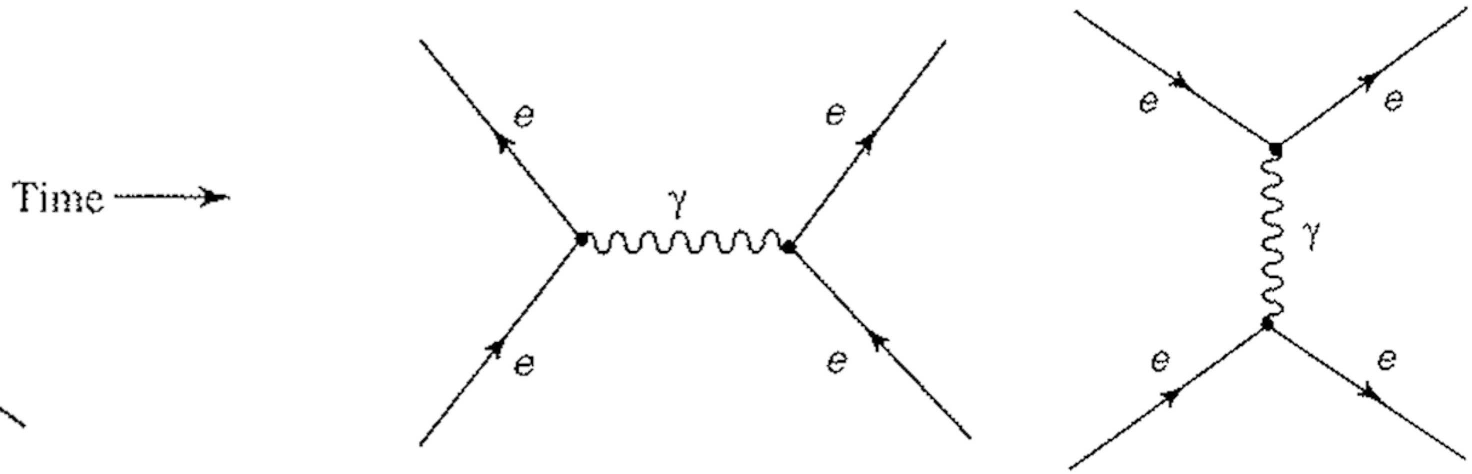
For gravity we do not yet have a quantum field theory.
More reading in the textbooks eg “Quarks and Leptons”

Quantum Electro-Dynamics QED

Interactions can be pictured/explained (calculated) by so called Feynman diagrams – invented for QED

Interaction vertex





Elementary diagram
Can be used to build up process
Examples ->

Some Rules:

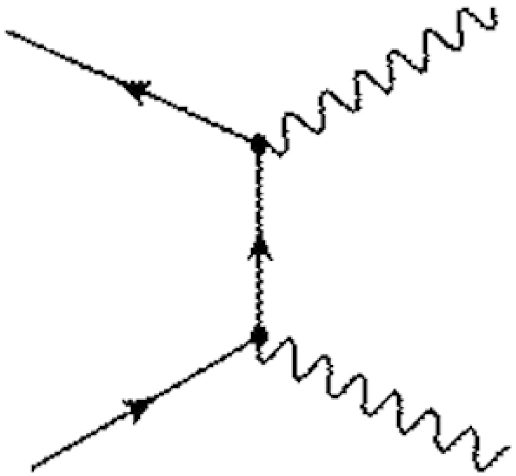
- Energy momentum conserved at each vertex
- Anti-particles run backward in time
- Only particles at the ends are observed
- Internal particles can be off-mass shell

Richard Feynman

parton model

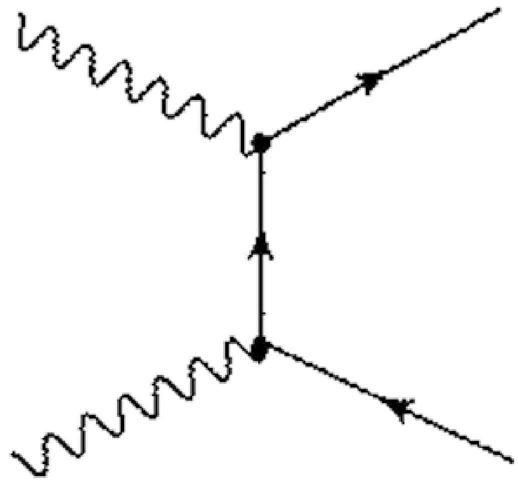
Quantum Electro-Dynamics QED

e+e- annihilation into two photons



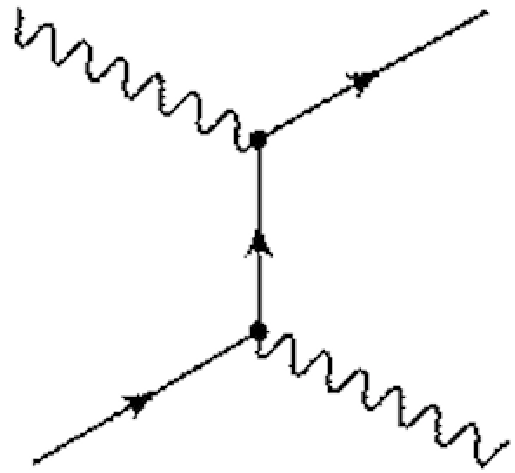
$e^- + e^+ \rightarrow \gamma + \gamma$

e+e- pair production



$\gamma + \gamma \rightarrow e^- + e^+$

Compton scattering



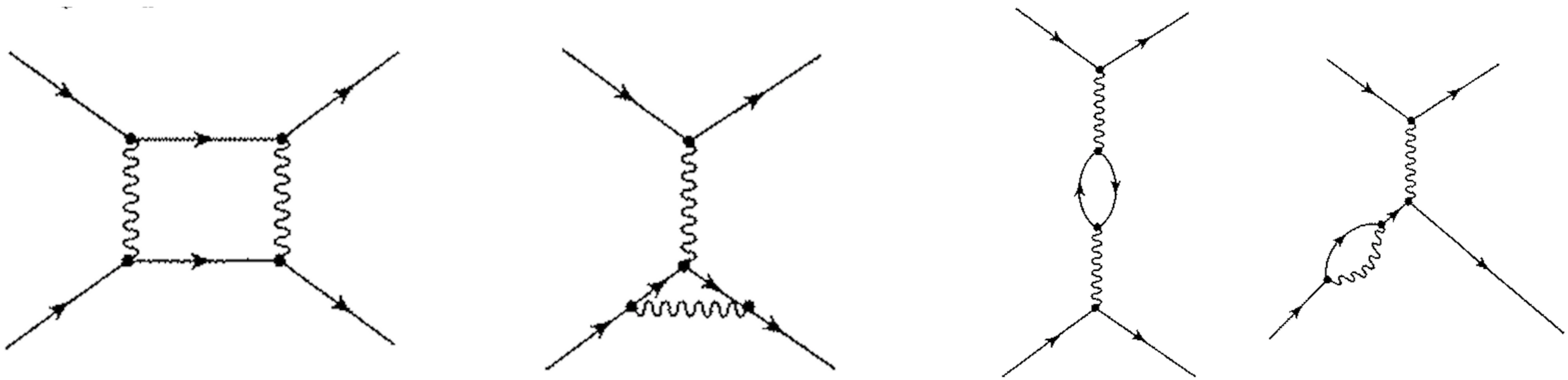
$e^- + \gamma \rightarrow e^- + \gamma$

Build from combinations of the elementary diagram

The Fundamental Forces of Nature

Caveat: The same final states will allow for more diagrams, ie by adding more interaction vertices. All diagrams always contribute. Hence in principle you have to calculate an infinite amount of diagrams

Examples with four vertices, but then consider 6, 8, 10… vertices

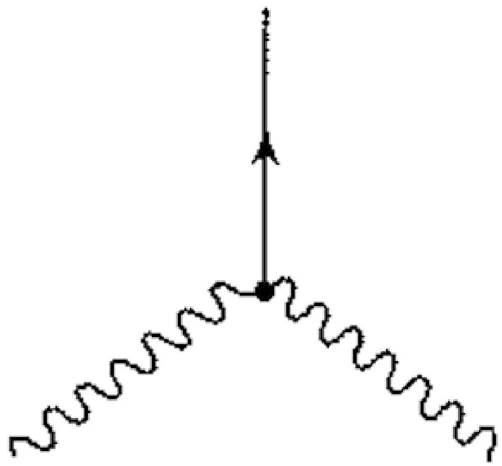


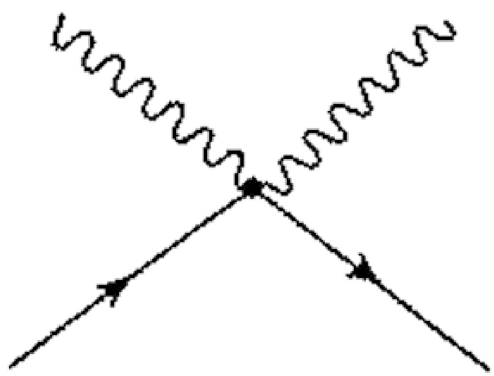
Rescue: each vertex introduces a factor

$$\alpha = e^2/\hbar c = 1/137$$

Hence, diagrams with more vertices will contribute less and less
One can truncate the series and get a precise result with few terms

Not Everything is Possible…!!





These are some forbidden diagrams…

At least in QED…
Maybe ok in some theory
Beyond the Standard Model

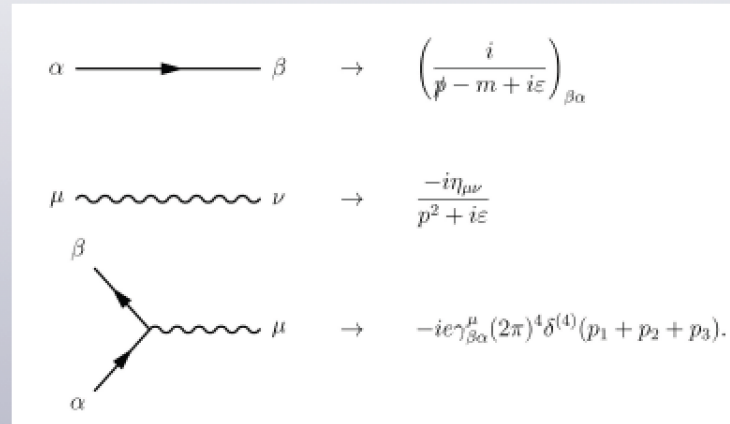
Quantum Electro-Dynamics QED

Details on the Feynman rules

Quantum Electrodynamics (QED)

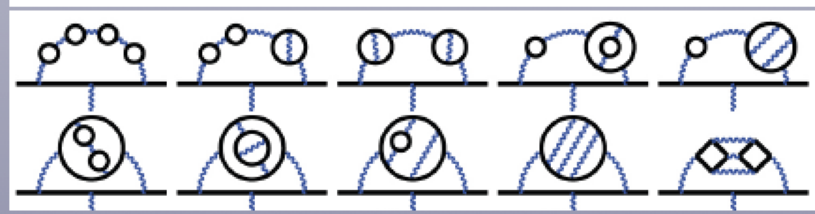
- The interactions of electrically charged particles are governed by **electromagnetism** (EM)
- Making sense of EM once **quantum corrections are accounted** for was a theoretical *tour de force* that ended in formulation of **Quantum Electrodynamics (QED)**
- Starting from **simple rules** (Feynman diagrams), compute terms at any order in the **perturbative expansion in the QED coupling**
- Some of the **most precise calculations ever done** have been obtained in QED: for instance, the **muon anomalous magnetic moment known better than one part in one billion!**

QED Feynman rules



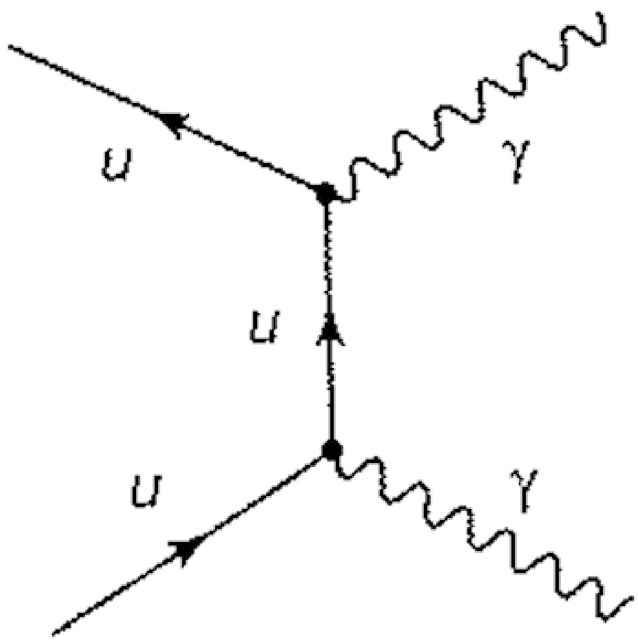
Feynman diagrams for muon anomalous magnetic moment

$$a_\mu^{\rm QED} = 116\,584\,718.09(0.15) \times 10^{-11}$$



Quantum Electro-Dynamics QED

The examples before were given for electrons and positrons, but they are general for all charged particles eg quarks and antiquarks



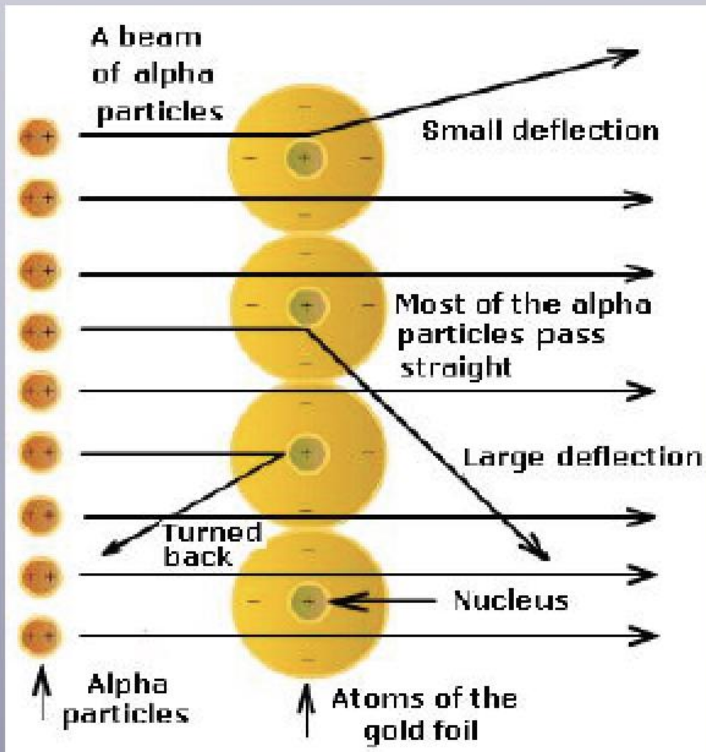
E.g. this diagram shows quark-antiquark annihilation into two photons

This process happens in Nature eg in pizero (π^o) decays.
The lifetime of the pizero is 10^{-16} sec

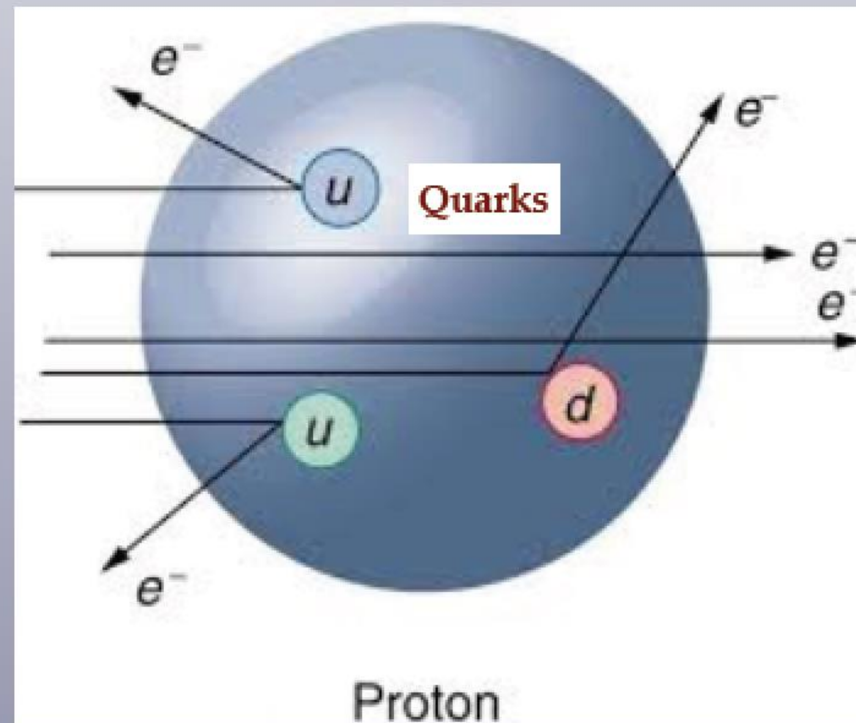
Quarks: the inner life of protons

- Scattering of α **particles (He nuclei) off atoms** lead in 1911 Rutherford to **discovery of internal structure of atoms**: a **point-like nucleus** and layers of electrons
- 70 years later, the **scattering of energetic electrons off protons** lead to equally surprising result: the **internal structure of protons**, composed by point-like **quarks**

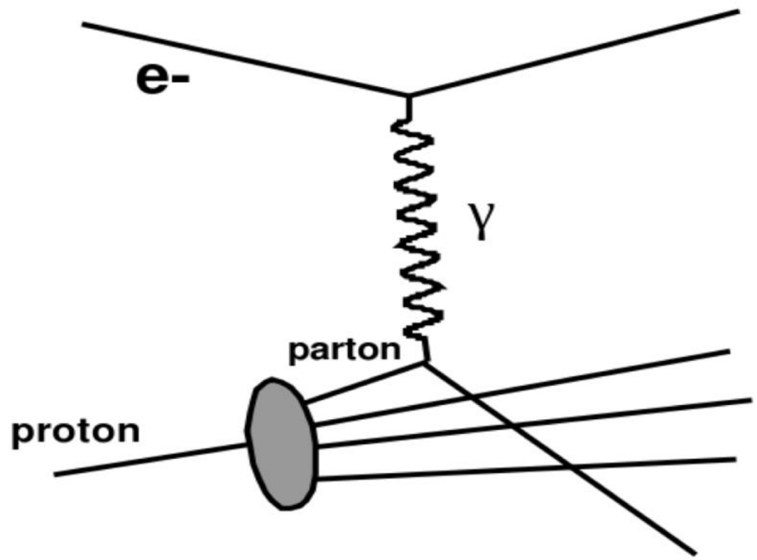
Rutherford experiment:
Atoms have internal structure!



Electron-proton collisions at Stanford Linear Accelerator:
Protons have internal structure!



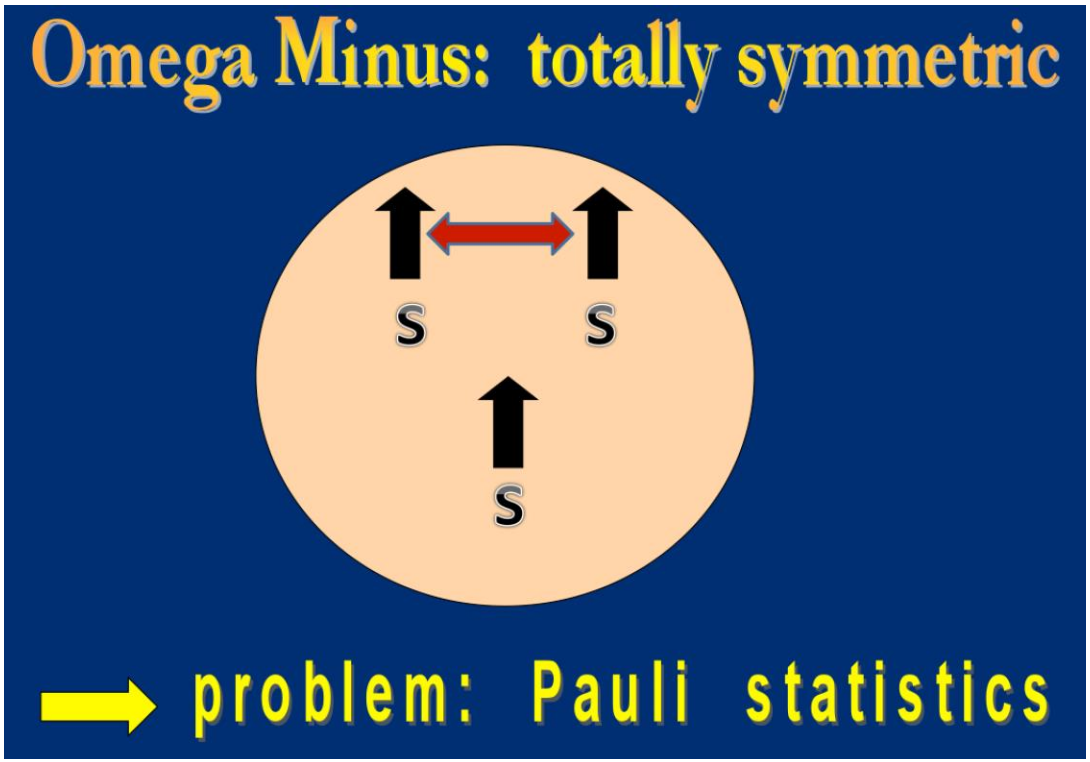
Problem1: Missing Momentum in the Proton



When we add up all the fractional momentum contributions in the proton as measured in deep-inelastic lepton-proton scattering we find that quarks only carry about ½ of the total proton momentum. Where is the rest of the proton momentum?

Problem2: Spin Statistics for some Baryons

Eg the Omega- particle which is a (sss) state
Two identical fermions cannot sit together in a state due to the Pauli exclusion principle which is fundamental in Quantum Mechanics



Quarks are fermions with a spin ½ ->
So two s-quarks can have different spin (one up, one down), but what about the third s-quark???

The Answer for all Problems

Revolutionary proposal:

Quarks come in 3 different varieties, called 3 different colors

This takes care of the factors 3 (9) that were missing before!!

Color is the ‘charge’ for the strong force

It is used to develop QCD in the image of the QED QF theory

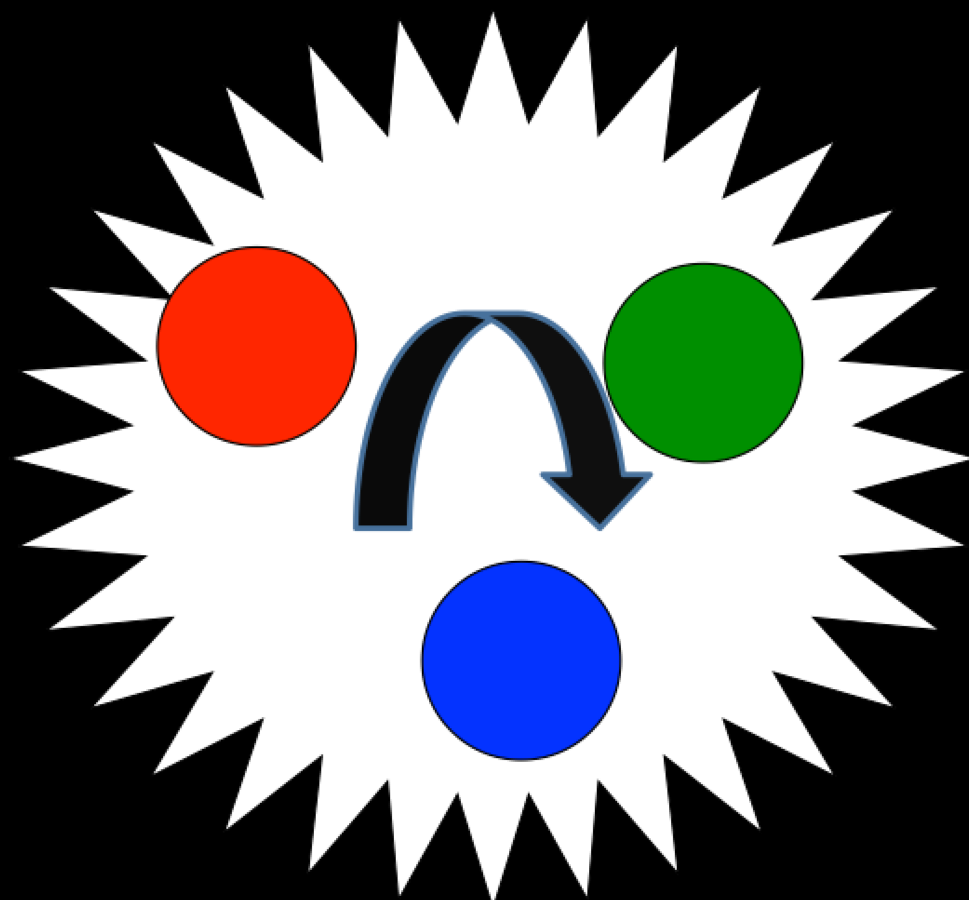
Additional hypothesis: All particles in Nature are colorless (white)!

Baryons: 3 quarks: red-green-blue -> white!

Mesons: quark-antiquark eg red-antired -> white!

hadrons – color neutral

proton =>white state



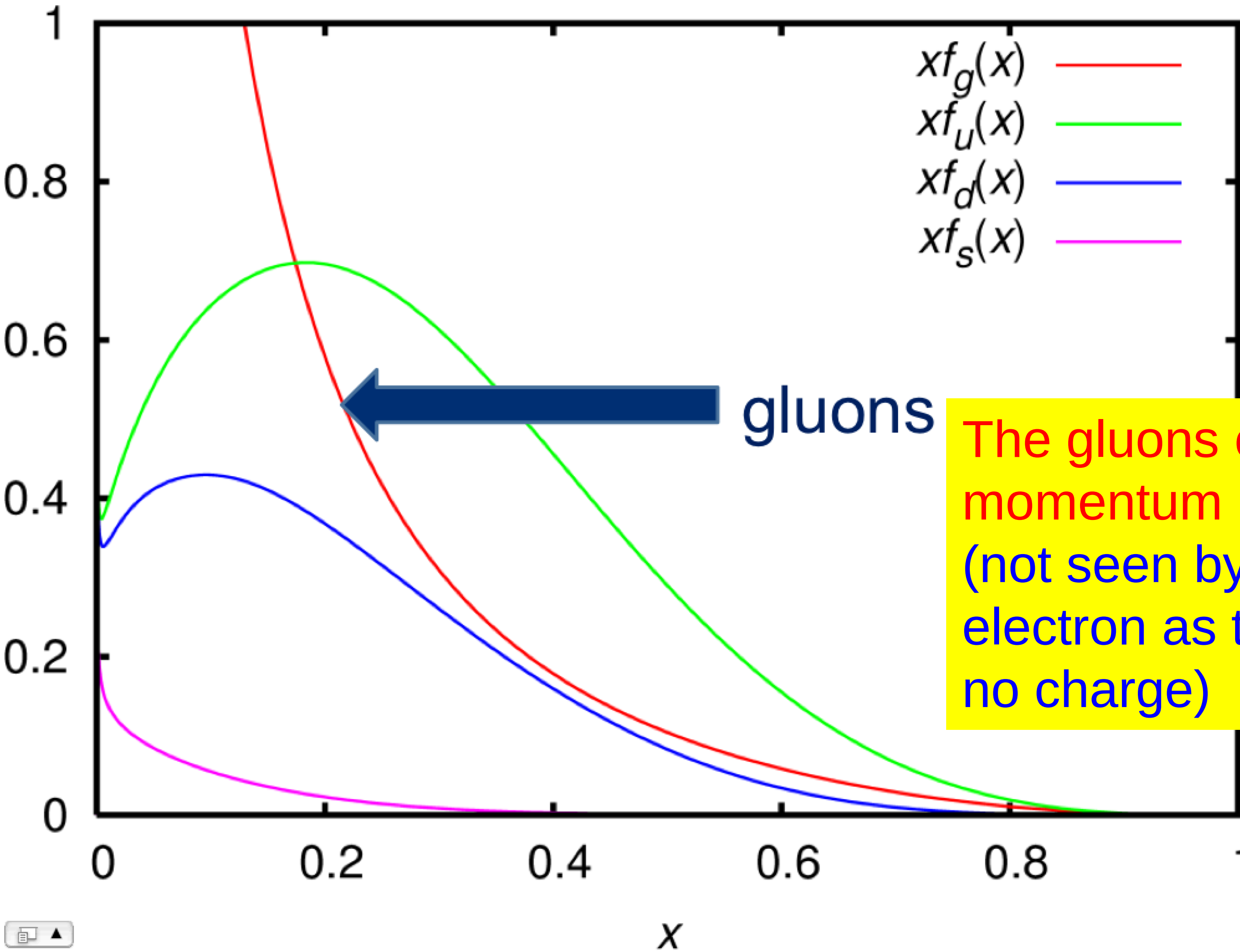
The Strong Force

The charge of the force is color
The force carrier is called the gluon. It is a spin-1 boson like the photon but there is an important difference: The gluon is also colored

8 massless gauge bosons

gluons

Problem1: Missing Momentum in the Proton



The gluons carry the missing momentum in the proton (not seen by the scattered electron as the gluon has no charge)

Technically: QED <-> QCD

QED:

$$L = \bar{q}\left[i\gamma_{\mu}(\partial^{\mu} + ieA^{\mu}) - m\right]q - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

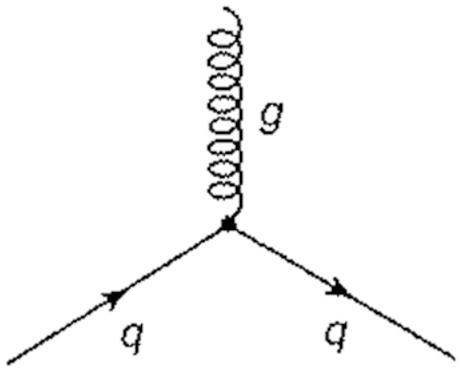
photon

gluons

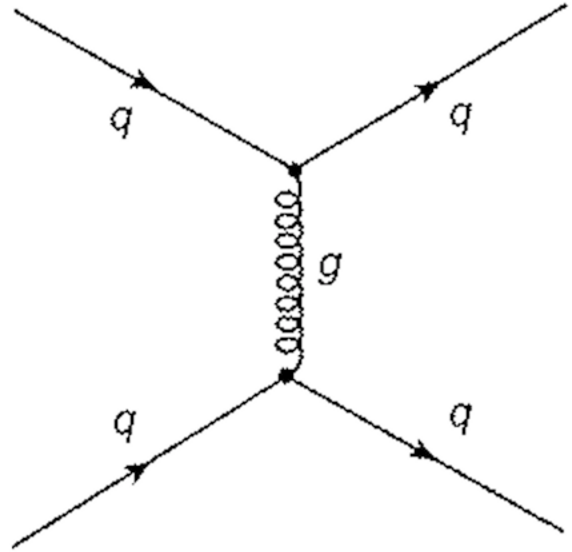
QCD:

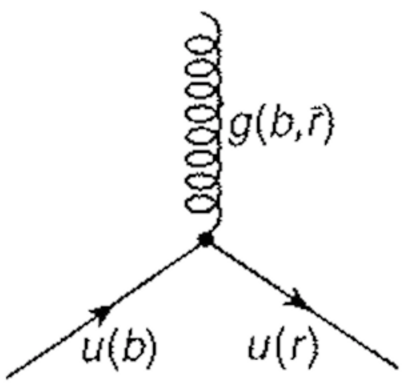
$$L = \bar{q}\left[i\gamma_{\mu}(\partial^{\mu} + ig\frac{\lambda^{a}}{2}A_{a}^{\mu}) - m\right]q - \frac{1}{4}G^{a}{}_{\mu\nu}G_{a}{}^{\mu\nu}$$

The Strong Force QCD



<- Elementary diagram
Can be used to
build up process
Example ->

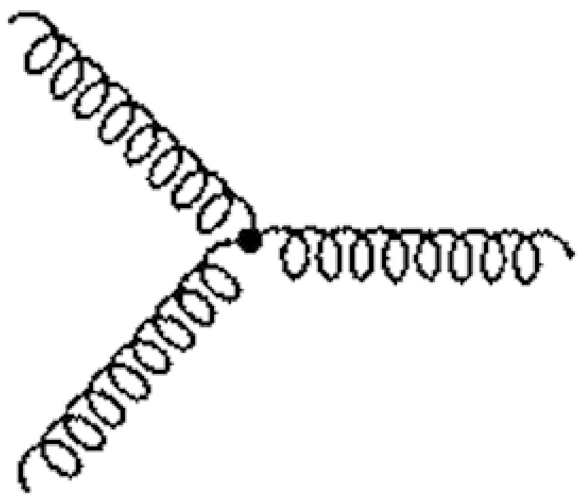


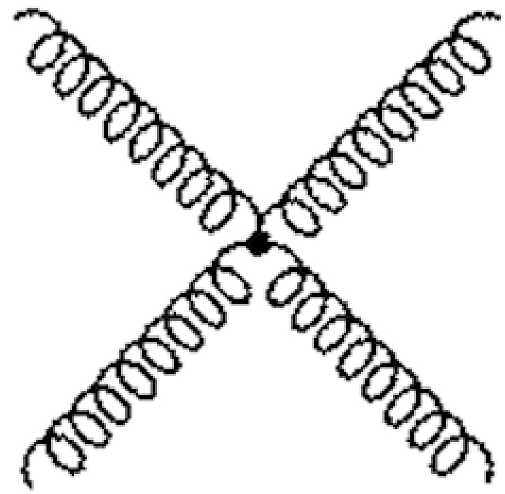


The gluons carry (double) color
Hence the quark can change color
(but not flavor) when interacting with gluon
There are in total 8 differently colored gluons

The Fundamental Forces of Nature

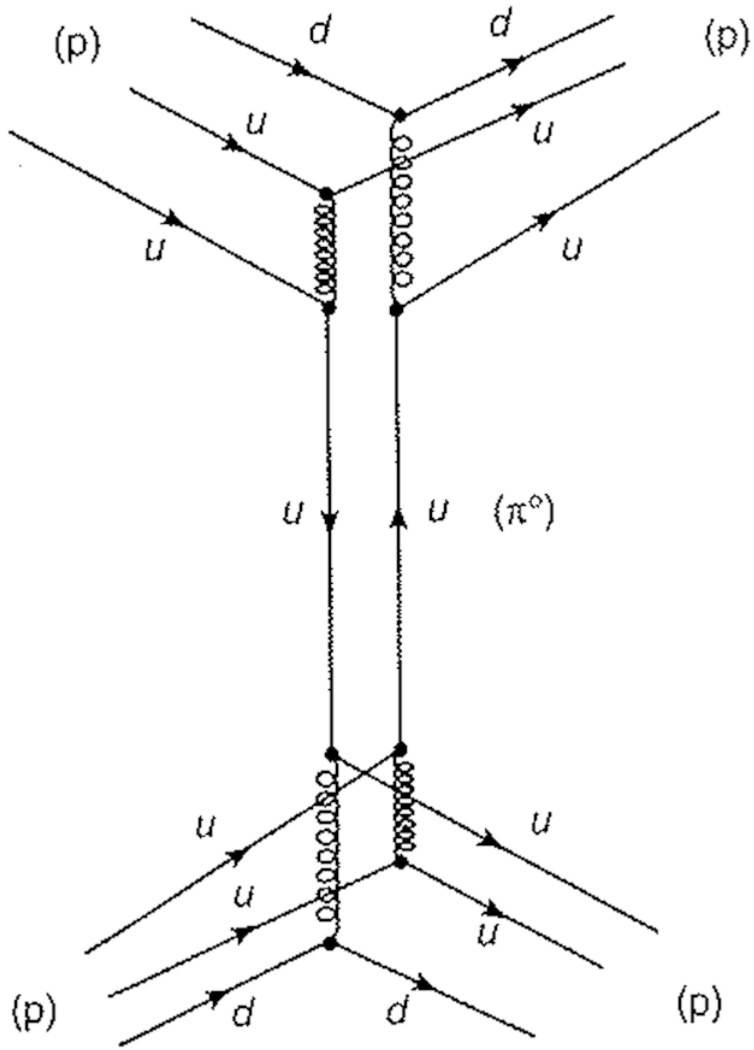
A new feature: gluons can self interact.
Photons cannot do that as they do not carry charge





As a result QCD is a so called Non-Abelian gauge theory
The symmetry group is non-commutative

Example of The Strong Force

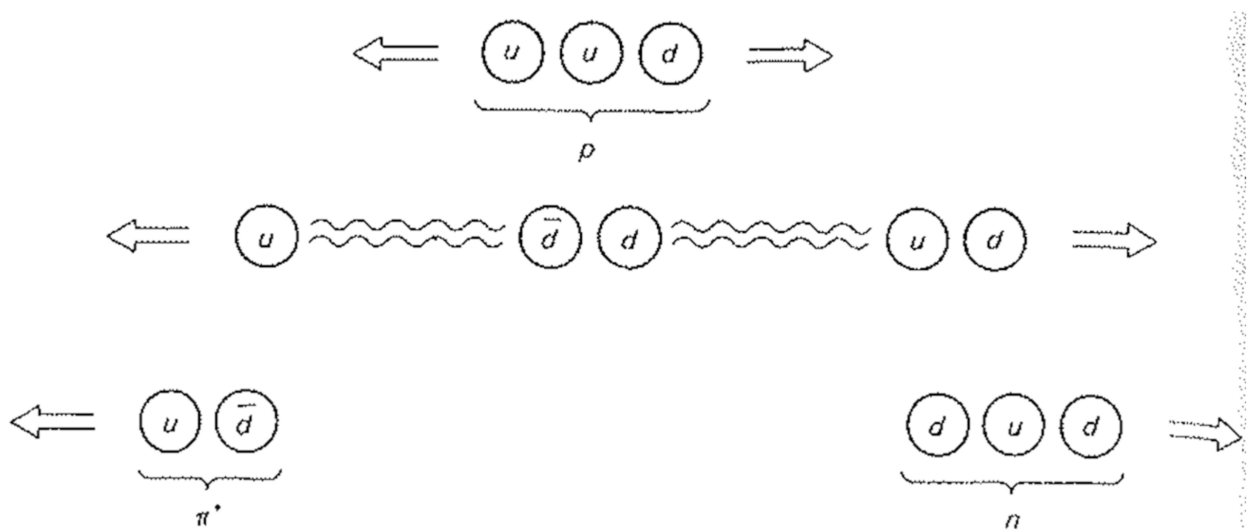


The strong force between two protons in the QCD picture

Compare with the meson approach from Yukawa who postulated the exchange of a meson…

The Fundamental Forces of Nature

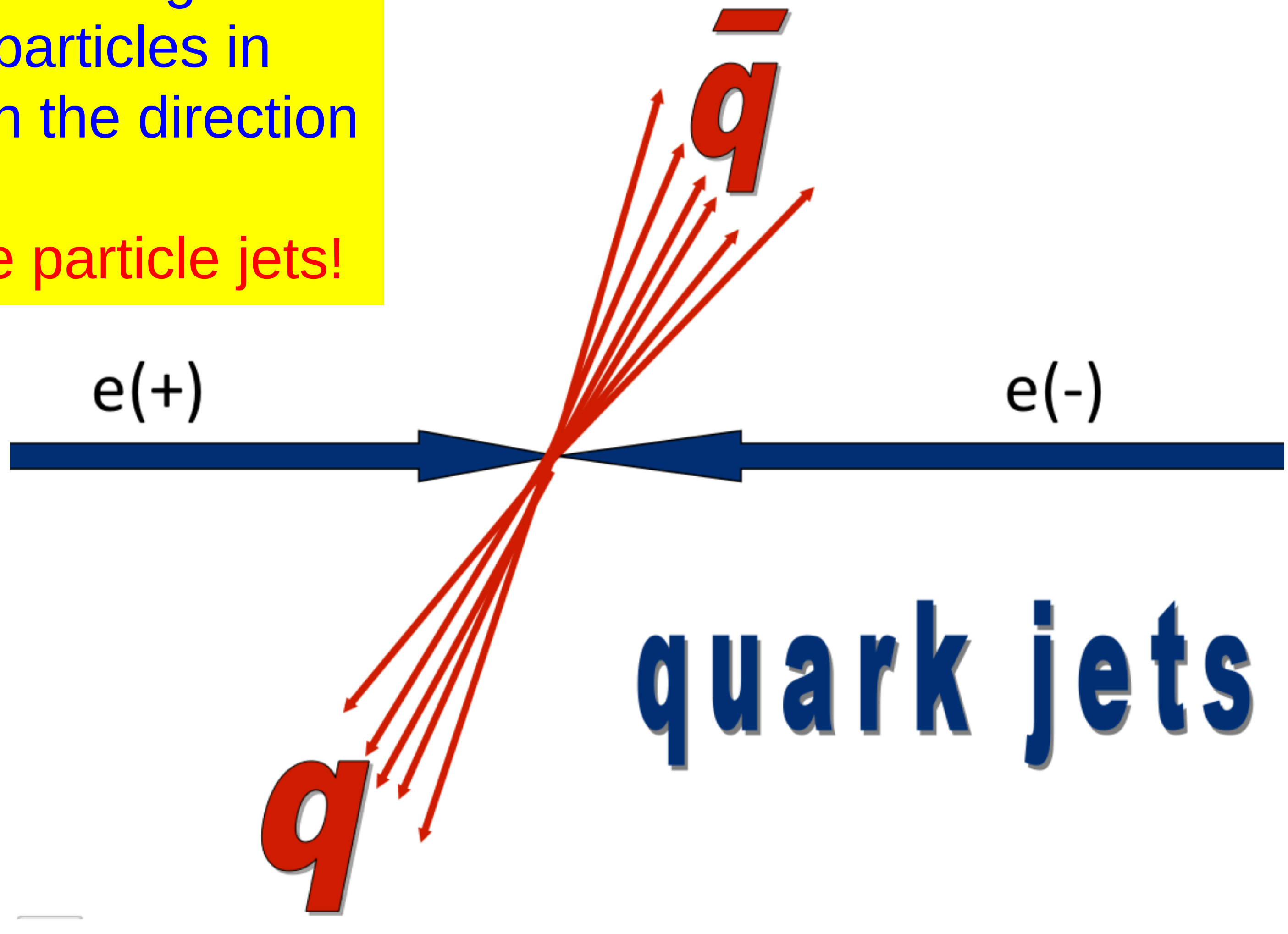
Why don’t we see free quarks?
Hypothesis: all particles in Nature are colorless!! (qq-bar, qqq)
When quarks separate, the force gets stronger and stronger between them (like in an elastic band)
At some point there is so much energy in that ‘band’ that it can break, creating new colour neutral hadrons on the way



Is that true also at the highest energies? We will check it at the LHC

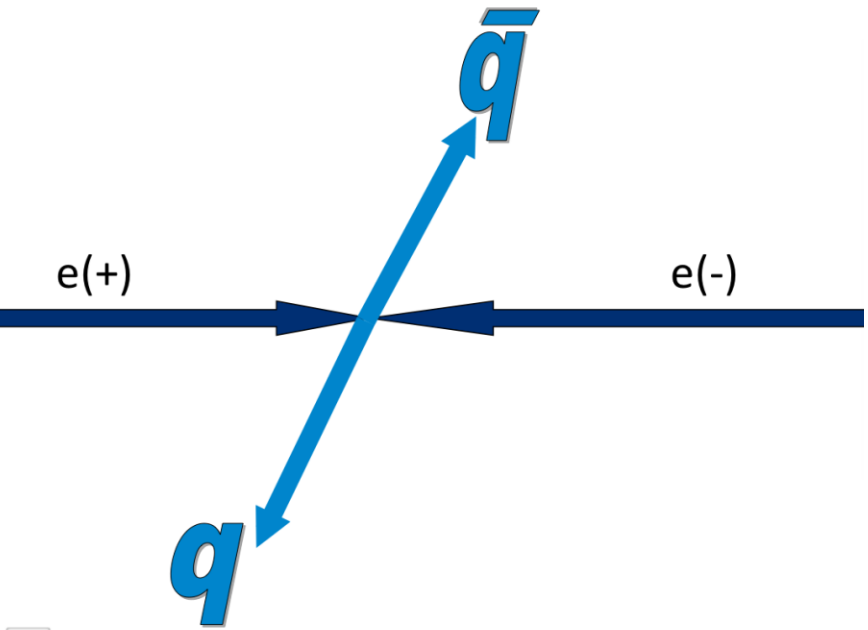
The Strong Force

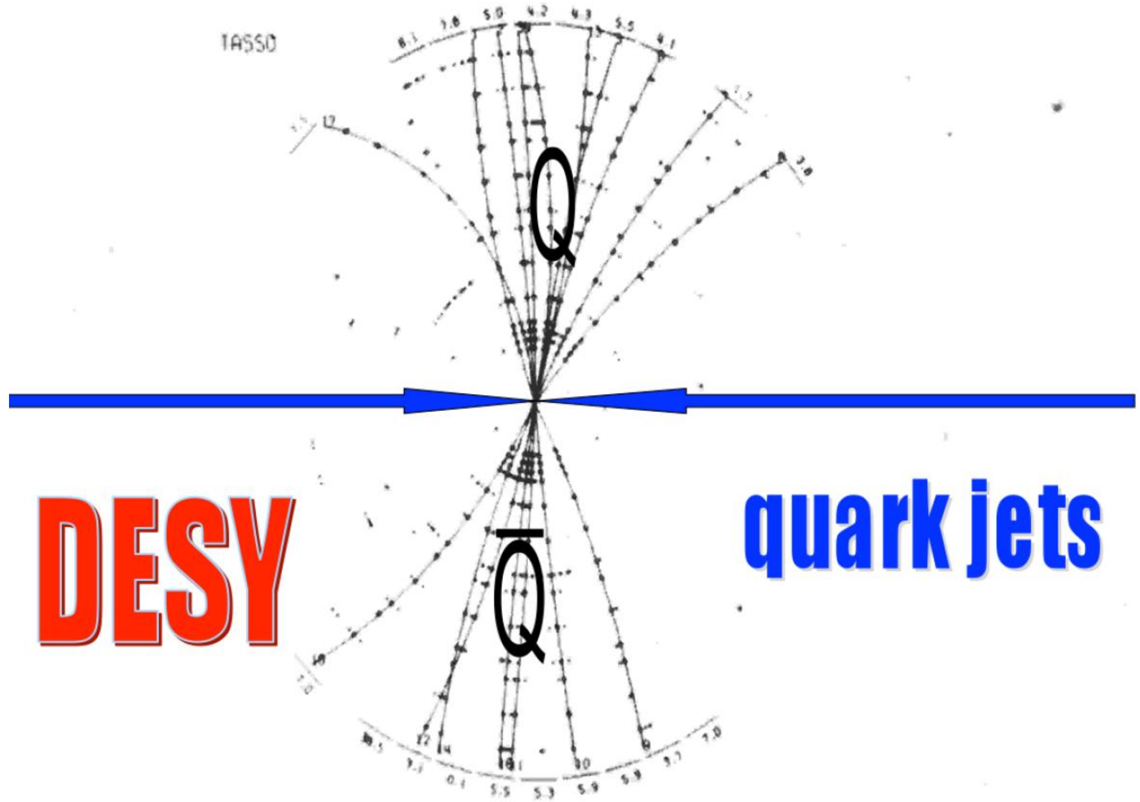
Consequence ->
When quarks emerge from a collision these will give a collimation of particles in a small cone in the direction of the quark
We call these particle jets!



The Strong Force

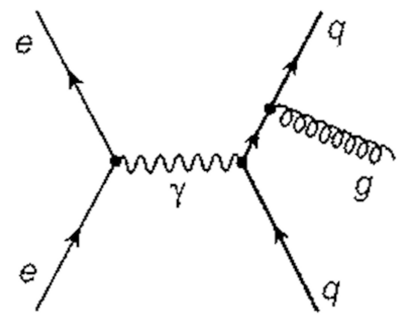
These jets have been experimentally observed eg in e+e- collisions

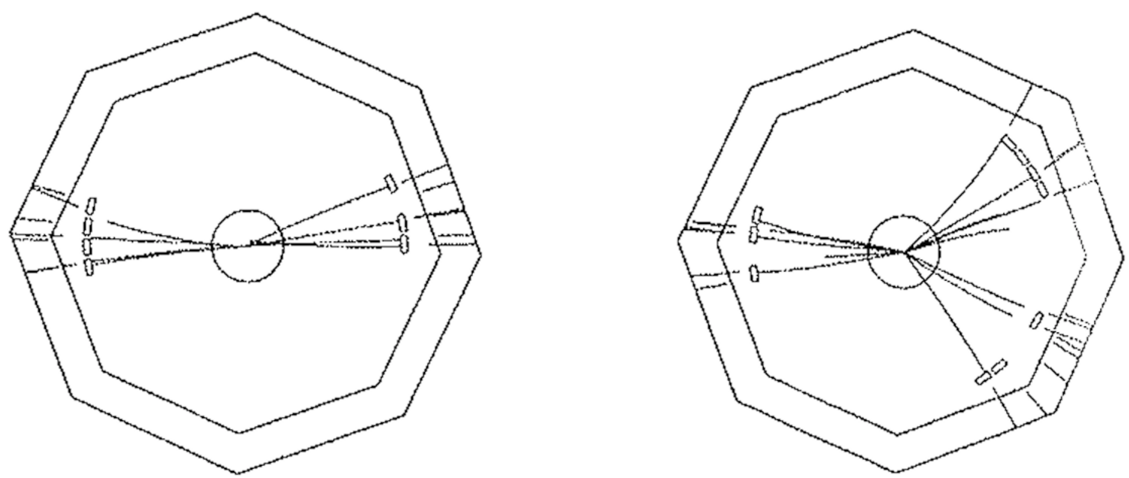




Can one observe Gluons?

Gluons are colored so (likely) cannot be observed free in Nature.
However we can see the effect of gluons in eg e+e- interactions.
The quark and gluons will lead to jets of particles in the detectors.
We expect 2 jet (all quarks) and 3 jet (quarks+ gluon) events

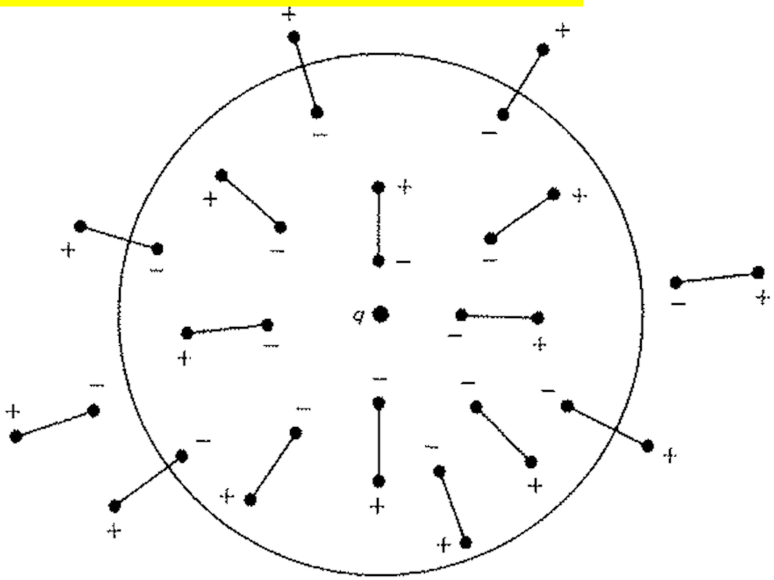


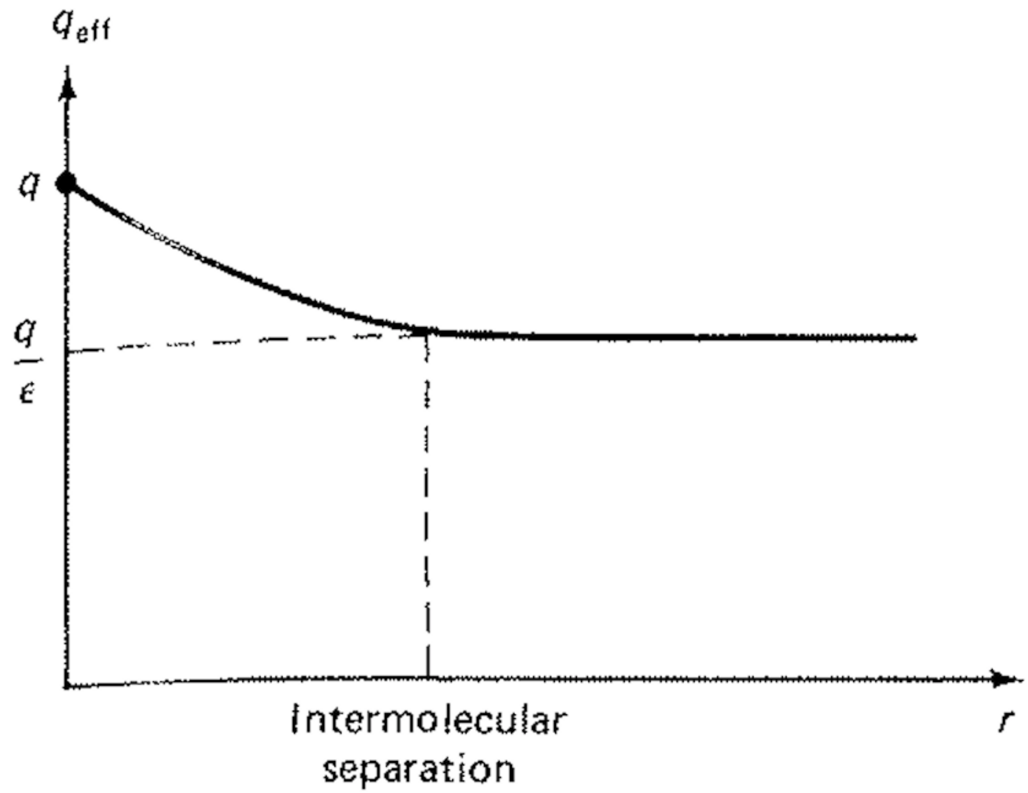


Vacuum Polarization

QED: The vacuum works as a dielectric for a bare charge. It shields the charge! Looking from a distance the electron charge is smaller than the ‘bare’ charge. Closer you see the true & stronger charge!

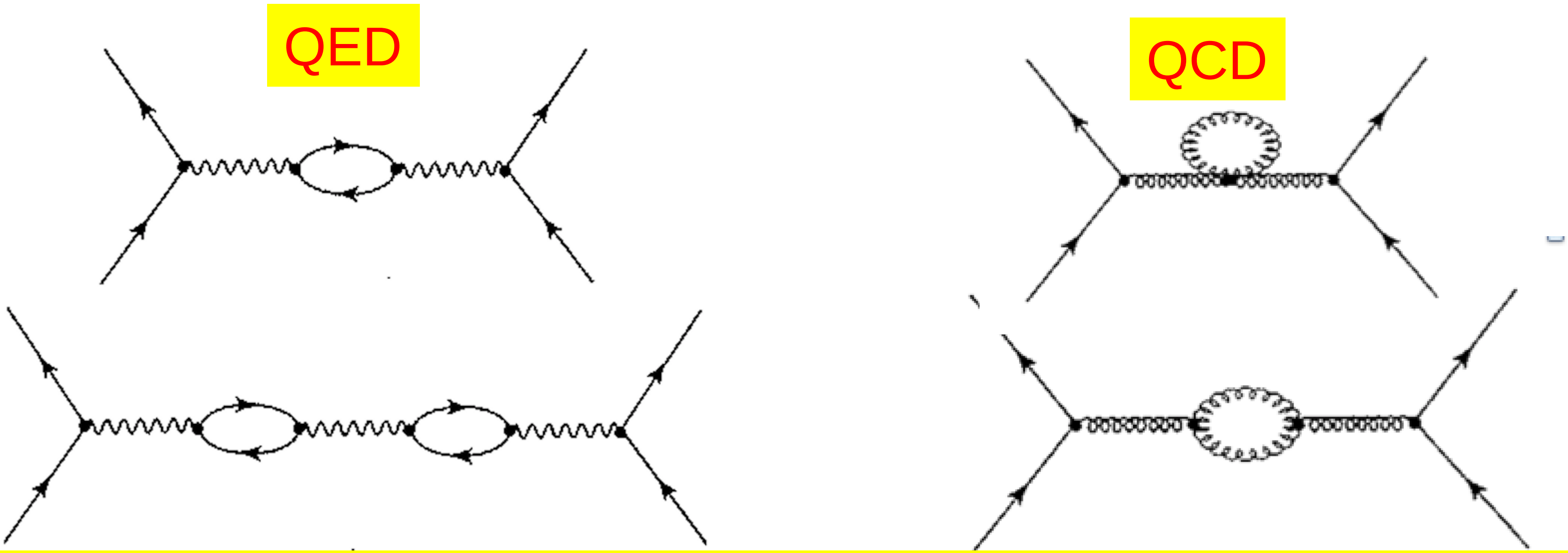
e+e- pairs from the vaccum





Is this also true for QCD?

The Fundamental Forces of Nature



For QCD it turns out that the quarks and the gluons have a different effect on the 'charge screening". The crucial parameter is

$$a \equiv 2f - 11n$$

f= flavours n= colors

If a <0 then the charge increase with distance. a = -21!

Hence in QCD the coupling strength is smallest for small distances

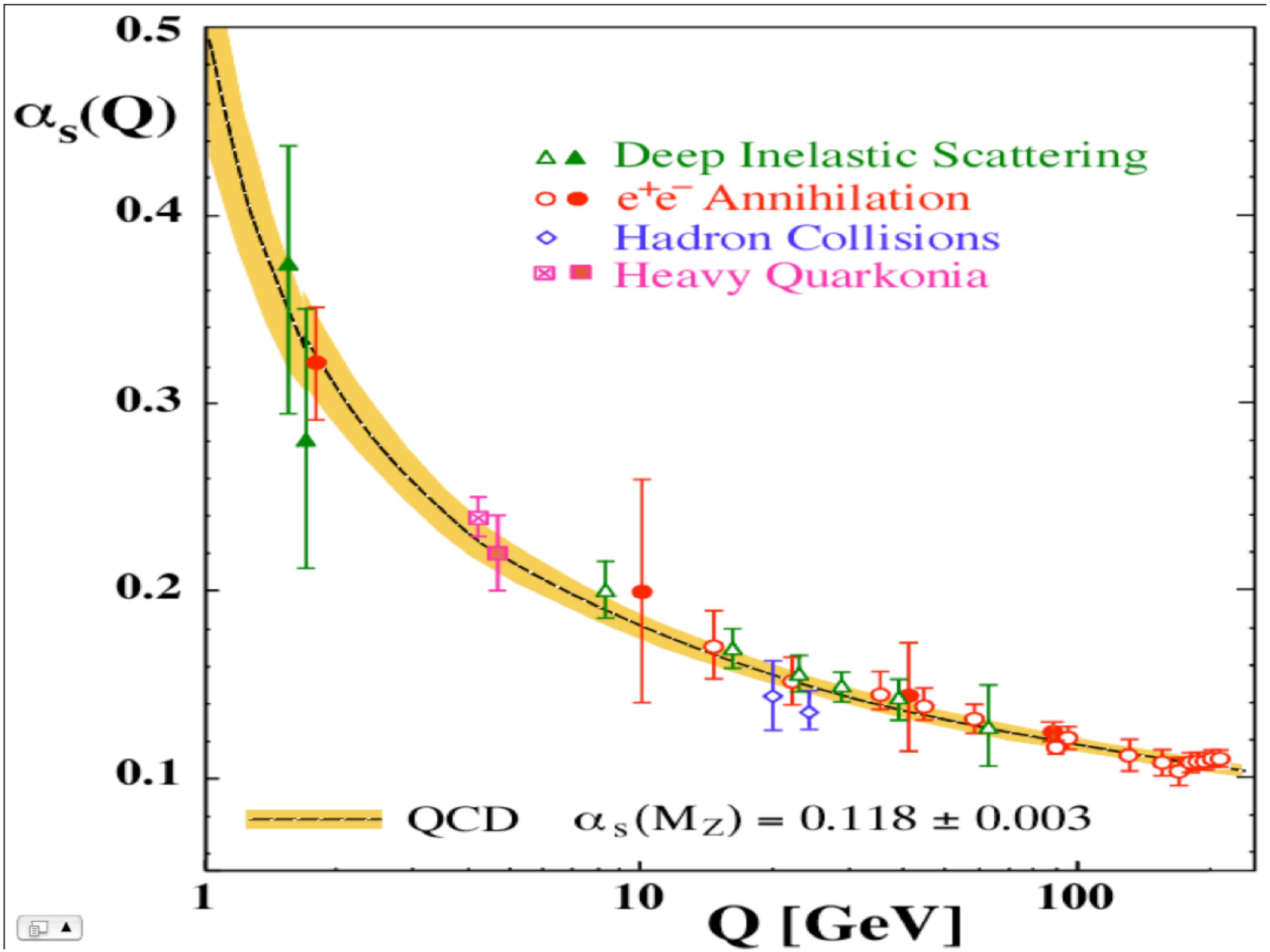
We call this "asymptotic freedom"

asymptotic freedom

coupling constant at inreasing energy ==> 0

Khriplovich 1968
t Hooft 1972
Gross, Wilczek 1973
Politzer 1973

The Strong Force QCD

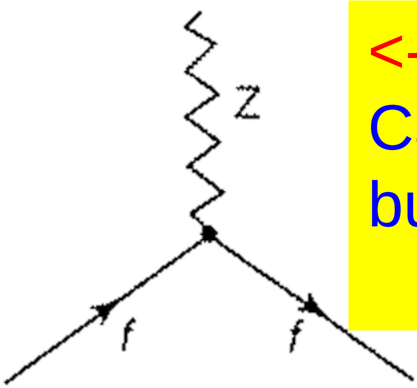


The coupling constant gets smaller for higher energy (shorter distance)

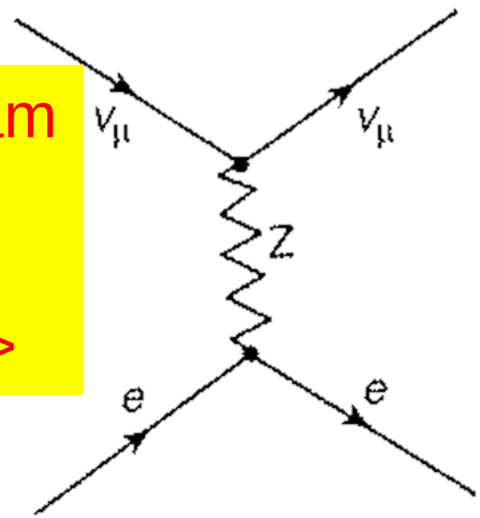
The Weak Force

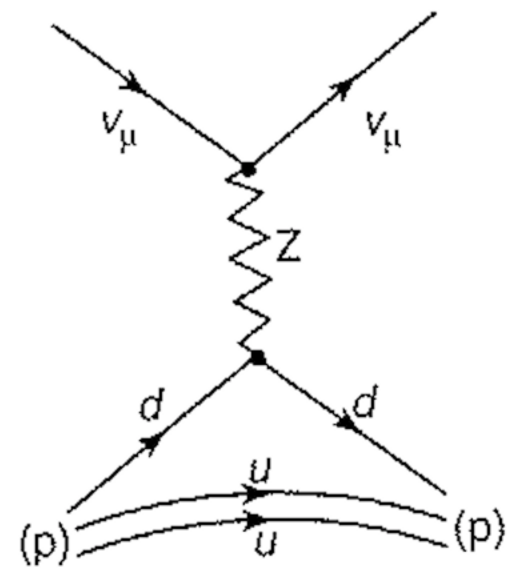
The discussion of the weak force deserves a full 2 hour lecture by itself.
Very well described in the text books, so will just give a summary

Weak neutral currents: Exchange of heavy Z boson (M_Z~ 90 GeV)



<- Elementary diagram
Can be used to
build up process
Example ->

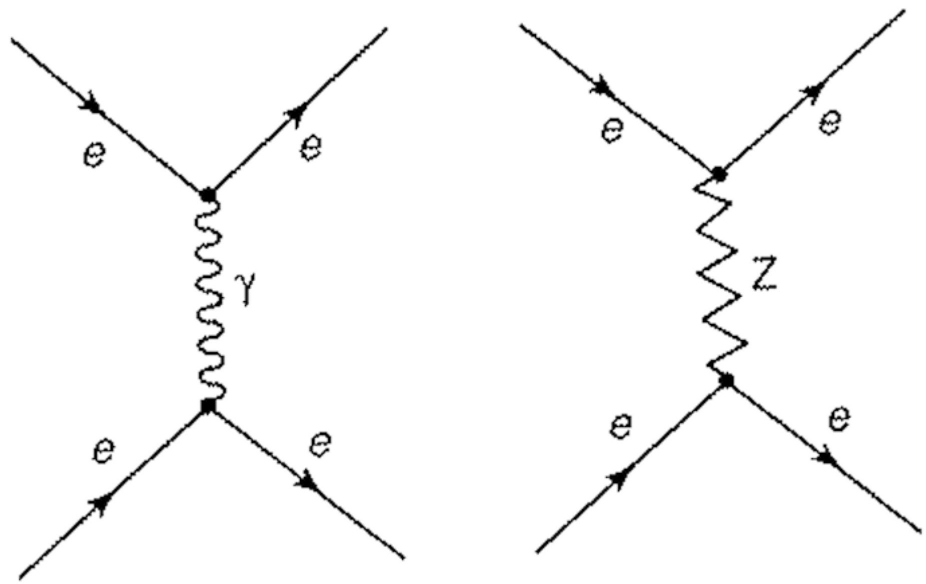




The heavy Z bosons were produced and discovered at CERN in 1983

The Weak Force

Any process mediated by a photon could also be mediated by a Z-boson

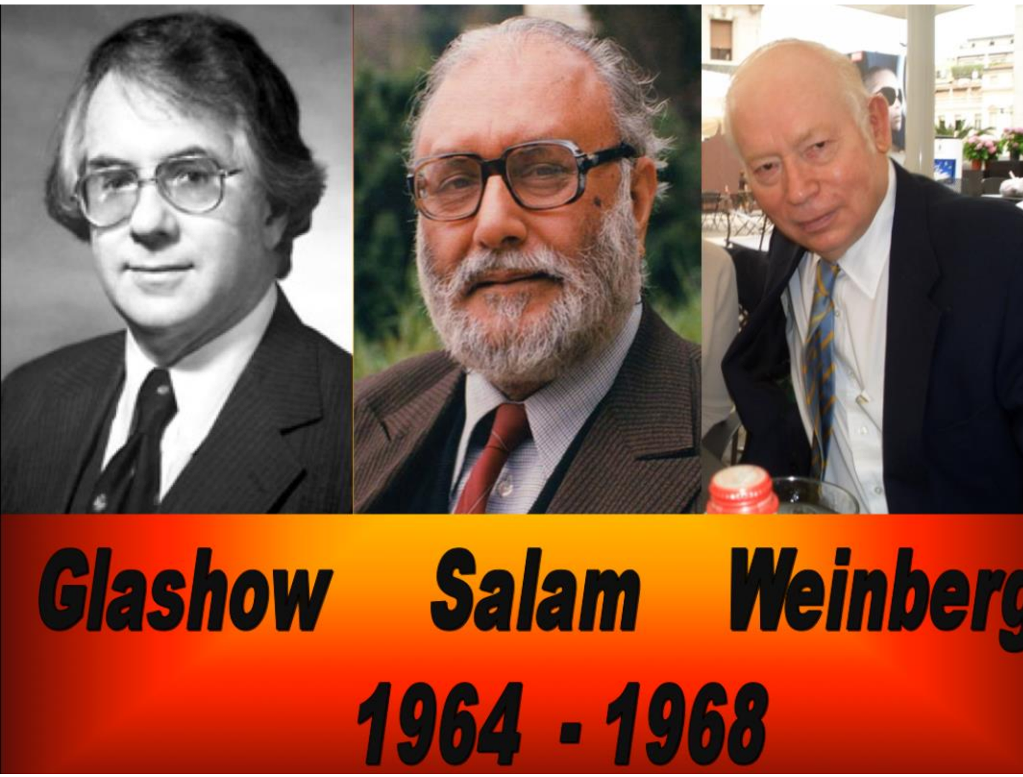


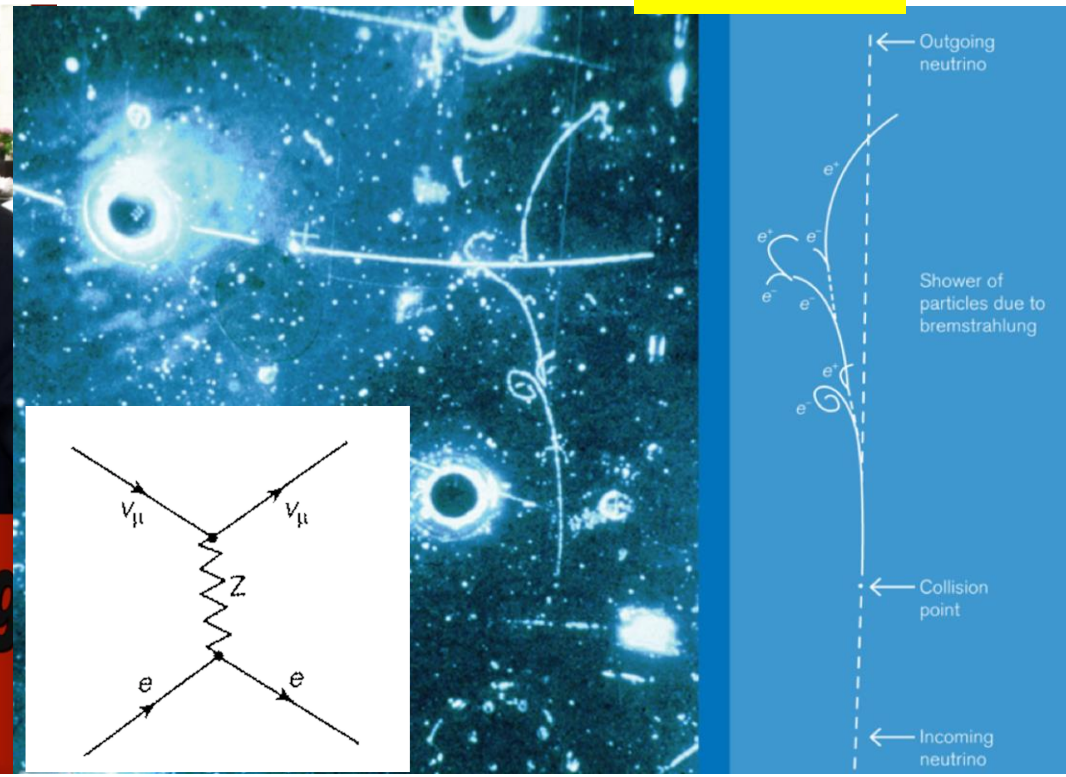
Important assumption: The electromagnetic and weak theory are both manifestations of the same underlying electroweak theory! The different observed effects are mostly due to the mass of the mediators (photon, Z, W particles)

Neutral Currents Discovered at CERN

Weak neutral currents were discovered in 1973 with the Gargamele bubble chamber, studying neutrino interactions

1973

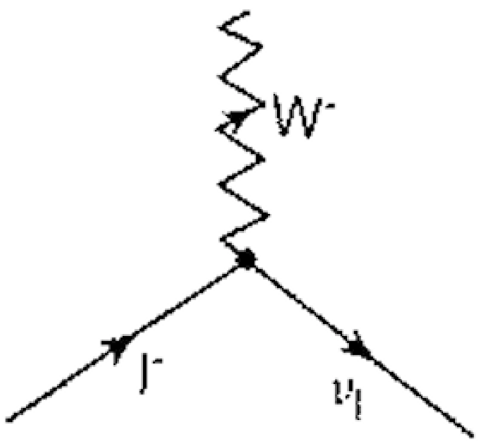


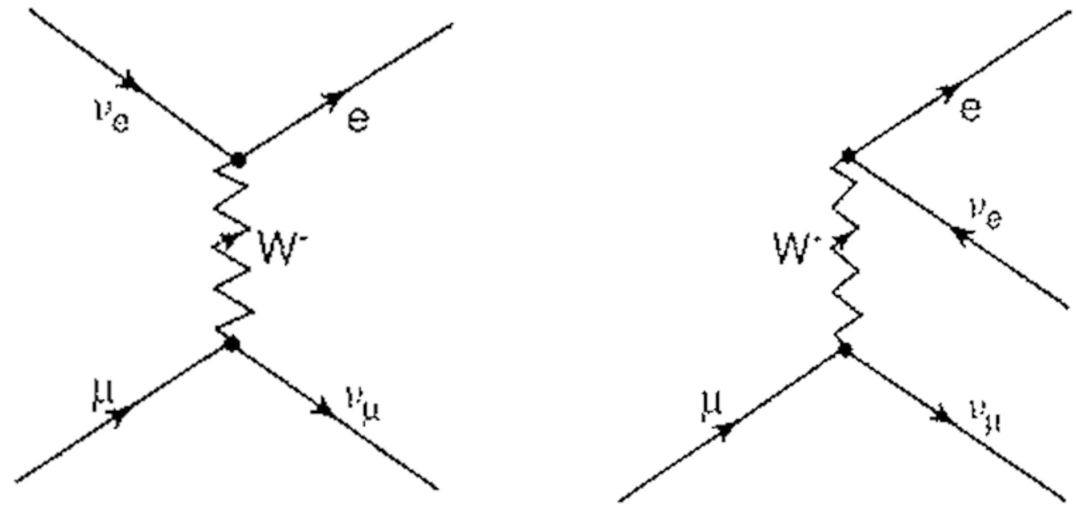


The verification of this prediction was crucial evidence for the electro-weak theory

The Weak Force

Weak charged currents: Exchange of heavy W boson (M_W~ 80 GeV)





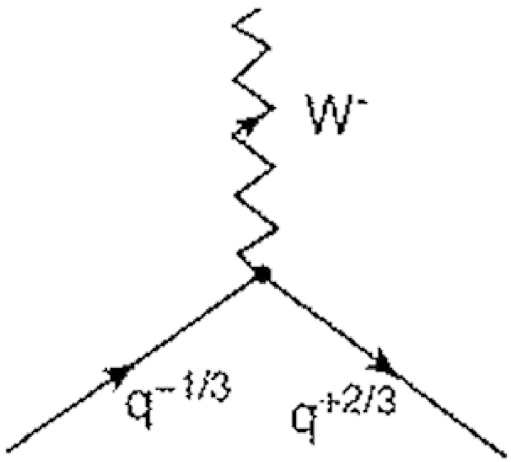
Elementary diagram
Can be used to
build up process

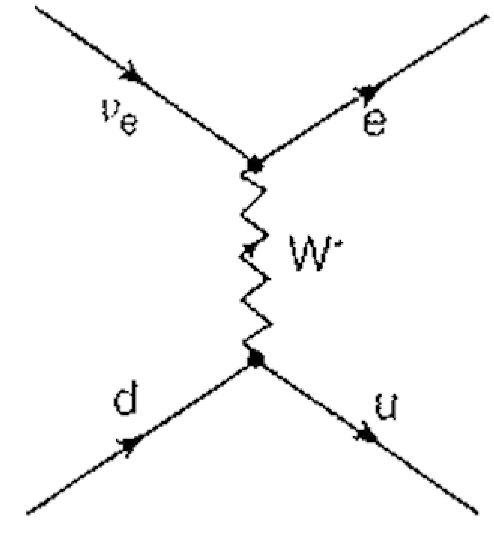
Examples
Neutrino-muon scattering
and decay of muon into
electron and two neutrinos

The heavy W bosons were discovered at CERN in 1983

The Weak Force

A very important feature of of the weak charged currents: these can change the flavor of the quarks (and leptons)



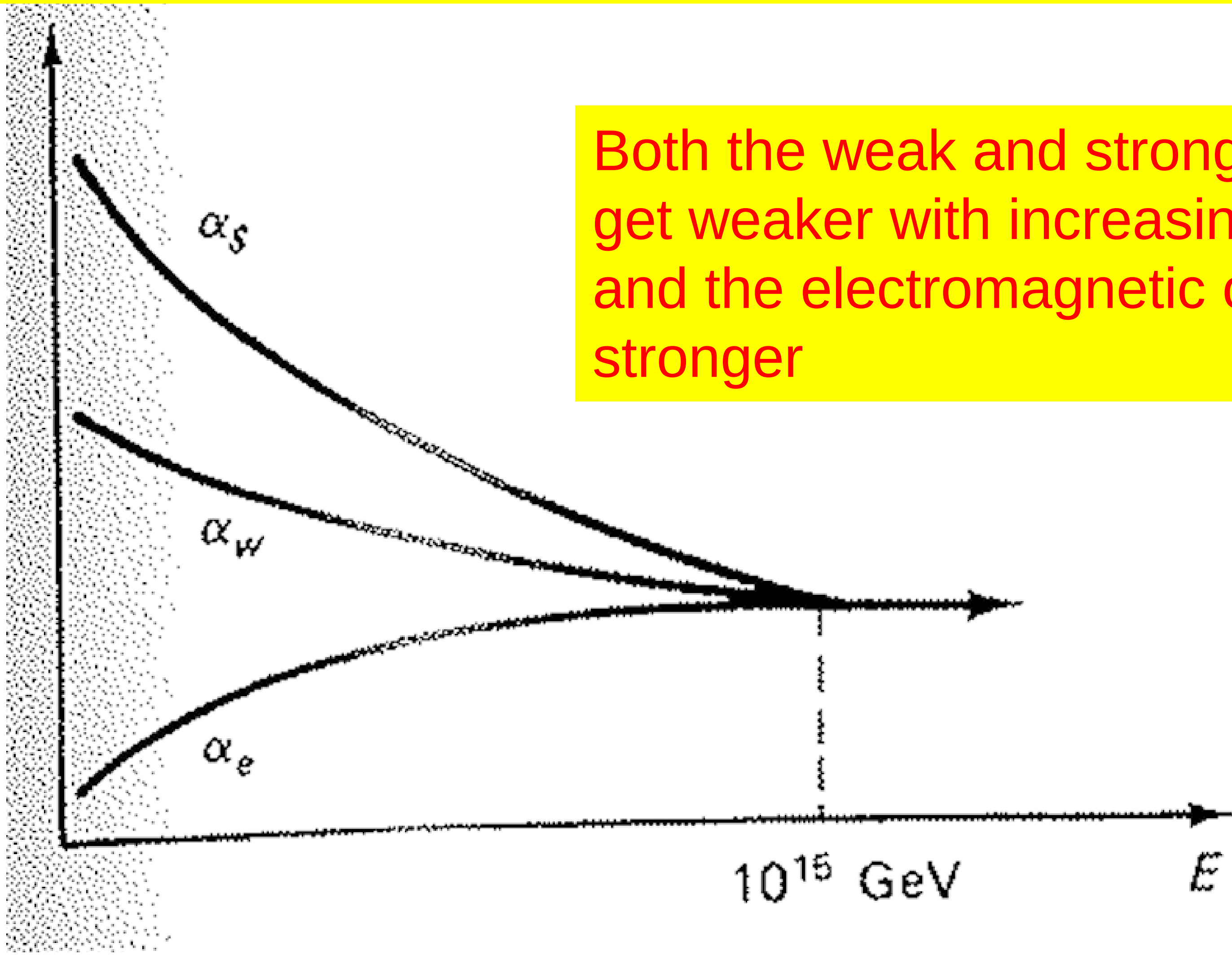


Eg a u-quark can turn into a d-quark after exchange with a W boson

Coupling Evolution with Energy

The running of the coupling constants with energy for the three fundamental forces

Both the weak and strong couplings get weaker with increasing energy and the electromagnetic one gets stronger



Symmetries

Strong force symmetry group

$$SU(3)$$

Electro-weak force symmetry group

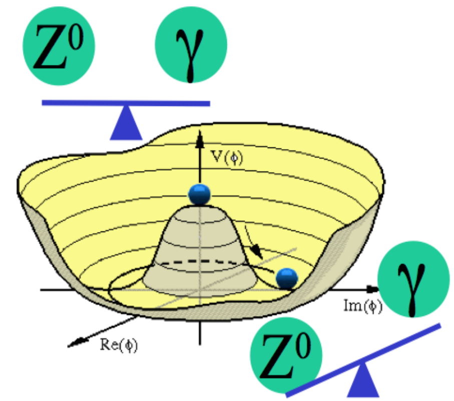
$$SU(2) \times U(1)$$

Standard Model symmetry group

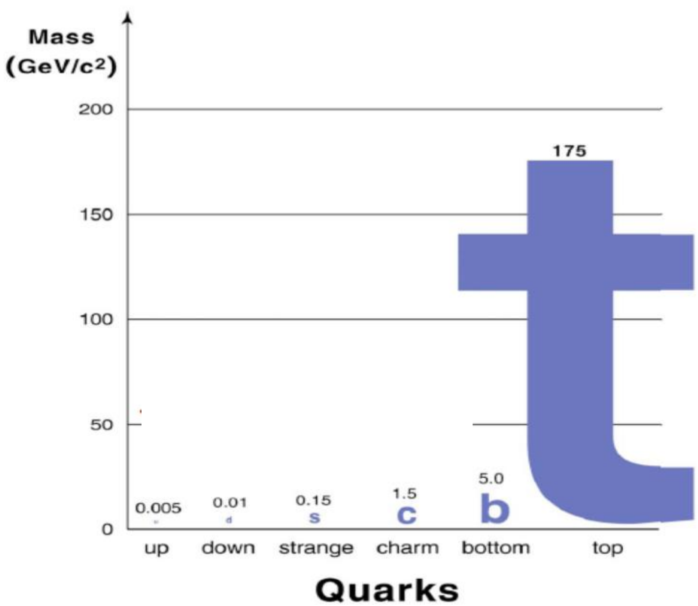
$$SU(3) \times SU(2) \times U(1)$$

The Origin of Particle Masses

- At ‘low’ energy the Weak force is much weaker than the Electromagnetic force: Electroweak Symmetry Breaking: ESB
- The W an Z bosons are very massive (~ 100 proton masses) while the photon is massless.
- The proposed mechanism(*) in 1964 gives mass to W and Z bosons and predicts the existence of a new elementary ‘Higgs’ particle. Extend the mechanism to give mass to the Fermions via Yukawa couplings.

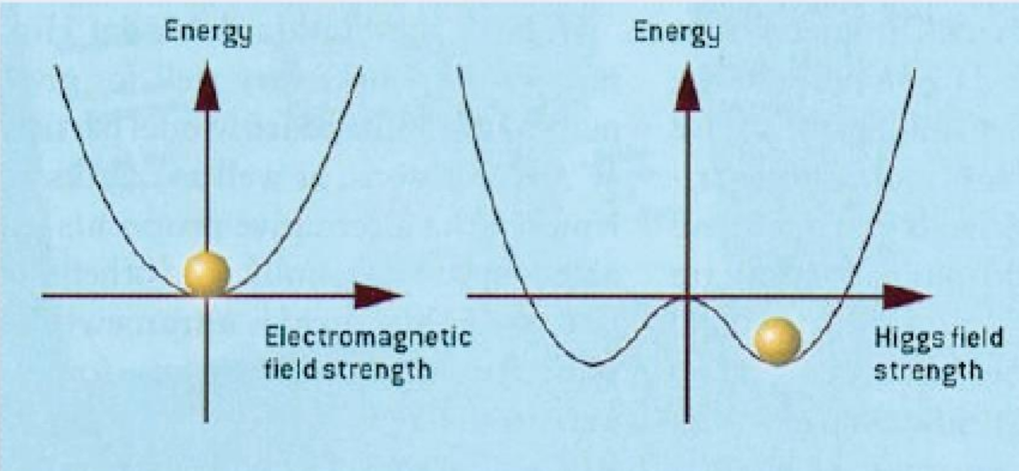


(*) Higgs, Brout Englert, Kibble, Hagen and Guralnik, and…



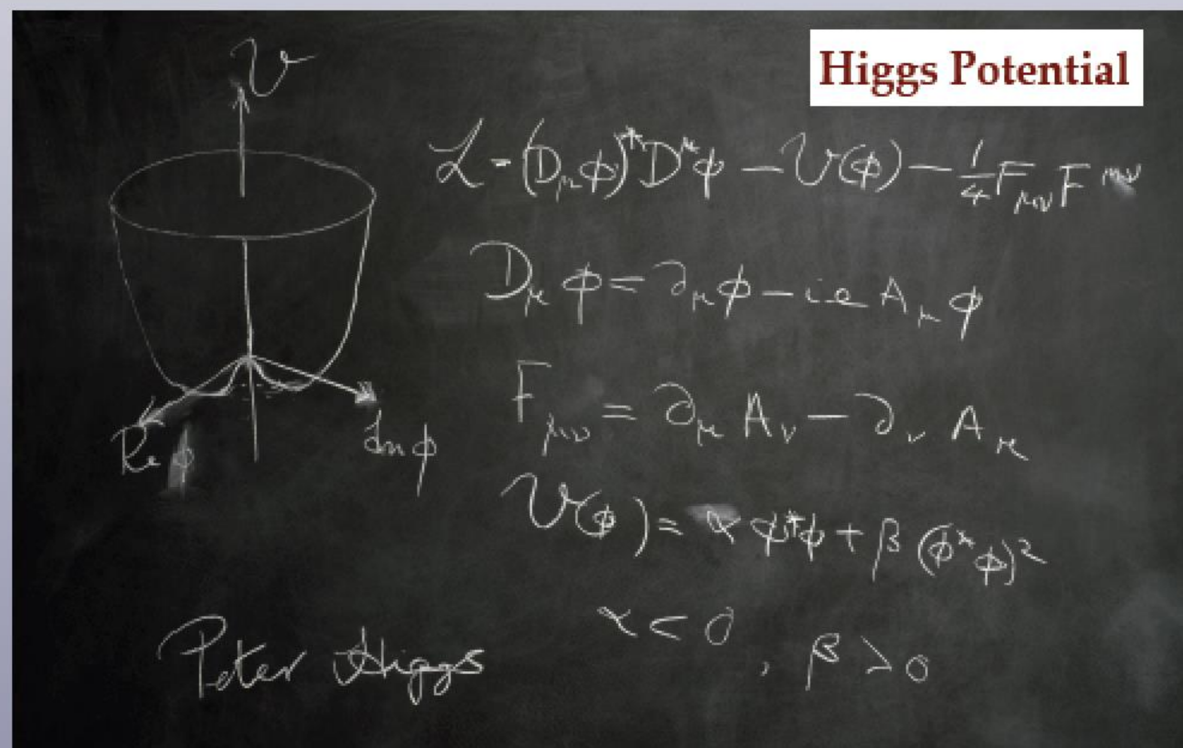
The Higgs (H) particle is the quantum of the new postulated field and has been searched for since decades at other particle colliders such as LEP and the Tevatron, and now found at the large hadron collider @ CERN.

The Higgs Mechanism



- In the SM, symmetries **do not allow mass terms** in the Lagrangian
- The Higgs **mechanism** bypasses this restriction: laws are still symmetric, but the **specific configuration** chosen by Nature (Higgs potential) is not**: Spontaneous Symmetry Breaking**

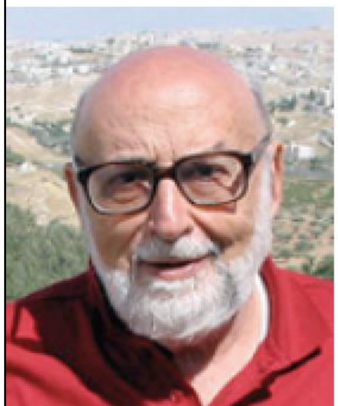
- Thanks to the Higgs mechanism, **SM particles can acquire a mass**
- As a byproduct, the **Higgs particle, excitation of the Higgs field** can also be produced if energy high enough
- Predicted more than 50 years ago, it was finally **discovered in 2012 at LHC**



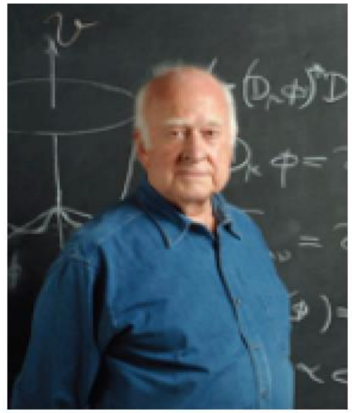
ESB Heroics

The year is 1964

Electroweak Symmetry Breaking


François Englert


Robert Brout


Peter Higgs


Gerald Guralnik


Carl Hagen


Tom Kibble

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland
Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

+ others could be mentioned that have inspired the above

The Hunt for the Higgs

Where do the masses of elementary particles come from?

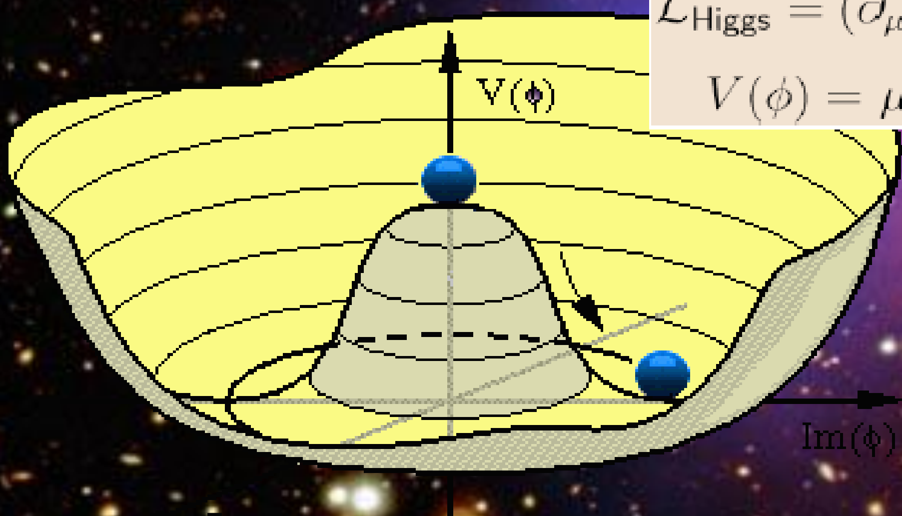
The key question (pre-2012): Does the Higgs particle exist? If so, where is the Higgs?

Massless particles move at the speed of light -> no atom formation!!

We did not know the mass of the Higgs Boson

$$\mathcal{L}_{\text{Higgs}} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi)$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



Scalar field with at least one scalar particle

Note: NOT the mass of protons and neutrons

It could be anywhere from 114 to ~700 GeV

The Mass of Particles

The Higgs Field gives mass to fundamental particles
What about composite particles like protons?

$$m_p \neq 2m_u + 1m_d$$

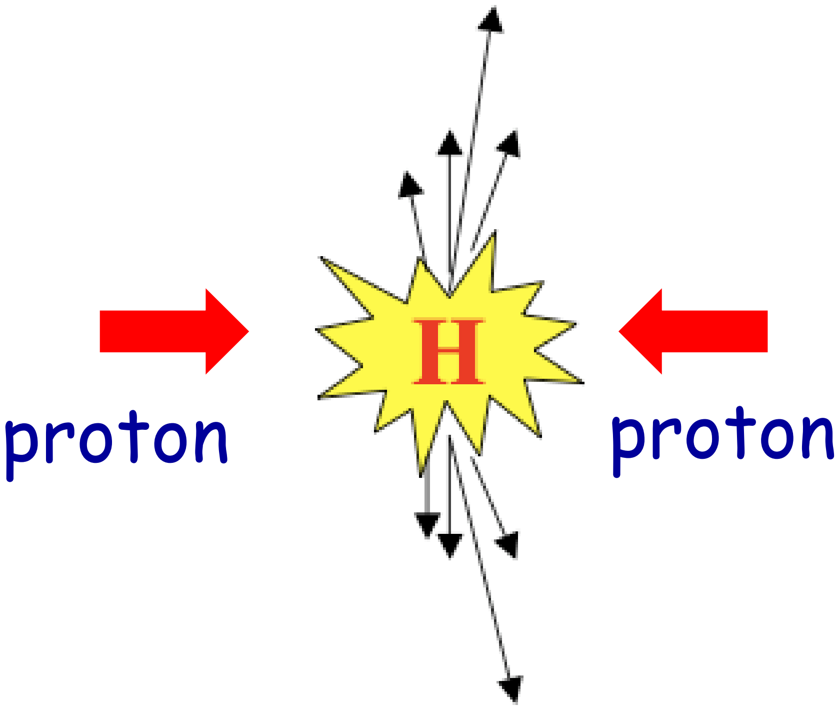
$$938.272\ \mathrm{MeV/c^2} \neq 2(2.3\ \mathrm{MeV/c^2}) + 1(4.8\ \mathrm{MeV/c^2})$$

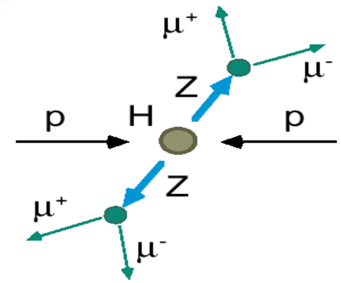
$$938.272\ \mathrm{MeV/c^2} \neq 9.4\ \mathrm{MeV/c^2}$$

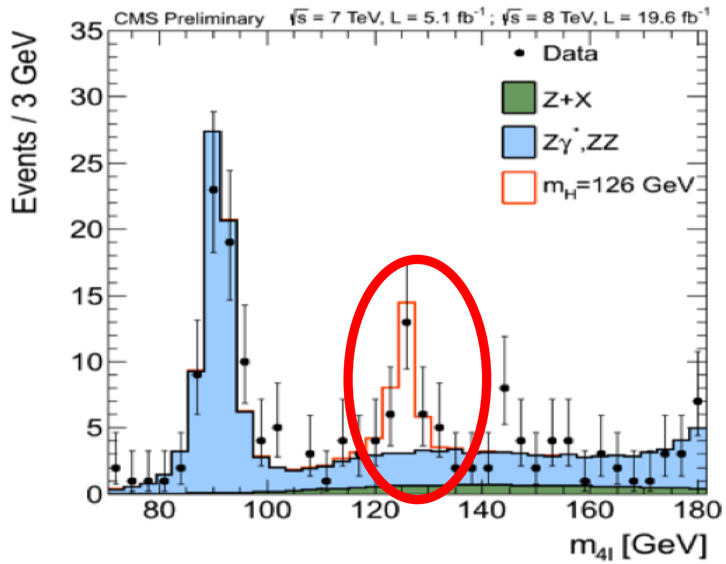
The Higgs makes up only ~1% of the mass of the protons
The remaining 99% comes from –strong force- binding energy of the quarks in the proton.

2012: A Milestone in Particle Physics

Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it



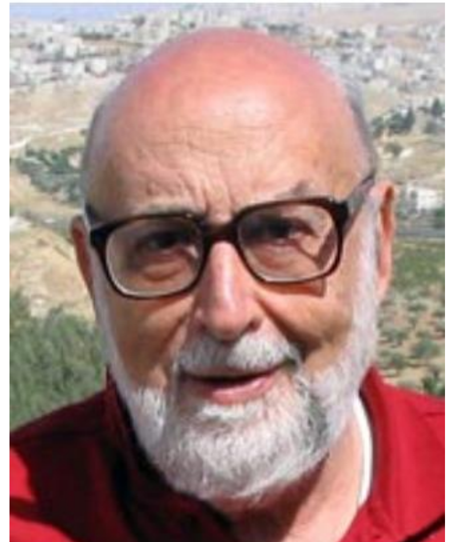




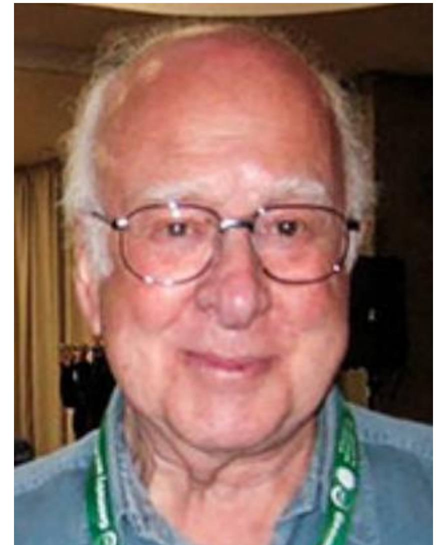
2013

The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

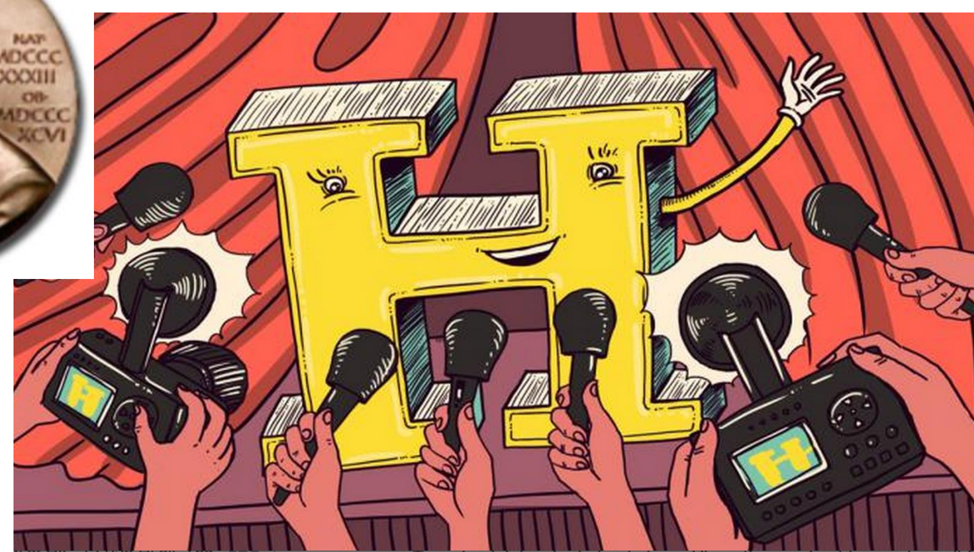
Tuesday 8 October 2013



Francois Englert

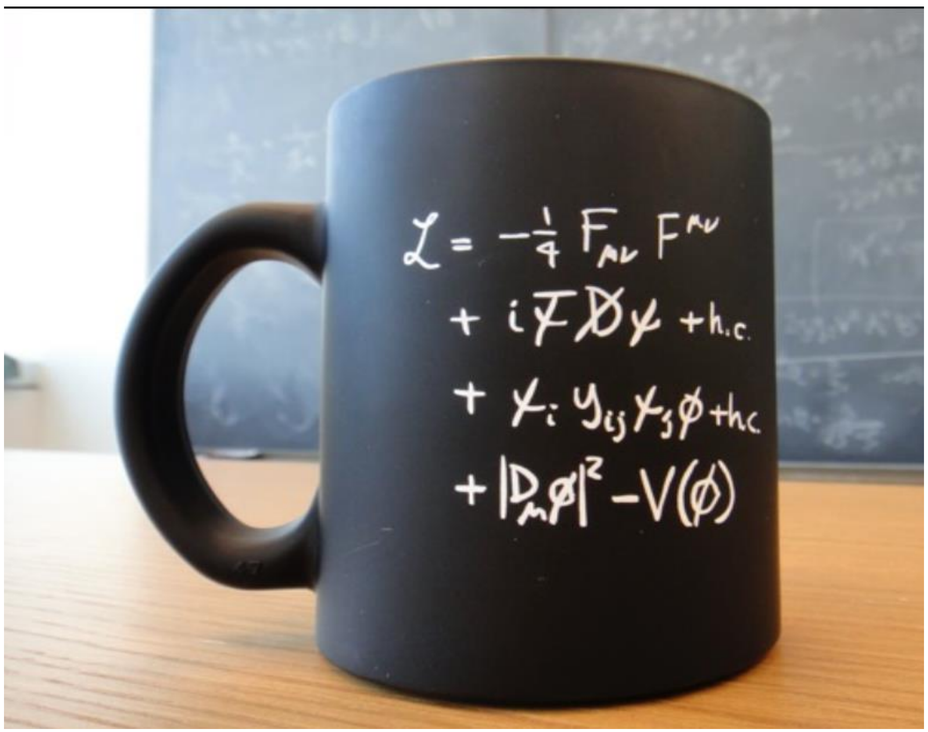


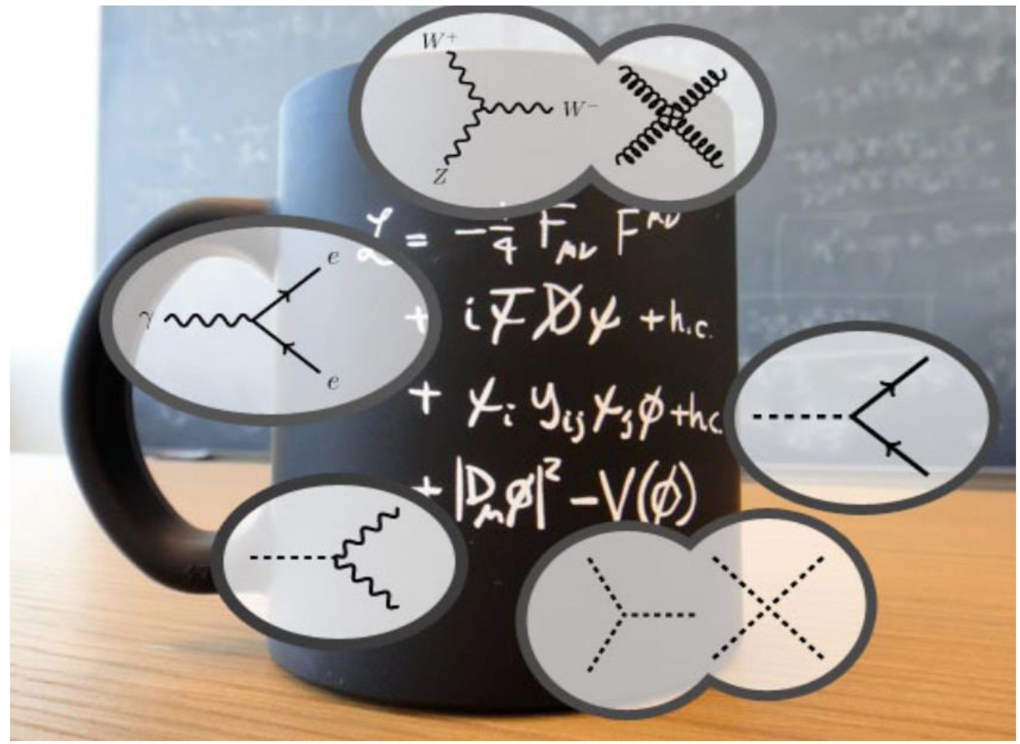
Peter Higgs



The Fundamental Forces of Nature

Our forces and interactions in particle physics are described by Quantum Field theories with special symmetry properties, so called gauge theories, which consist of gauge fields…

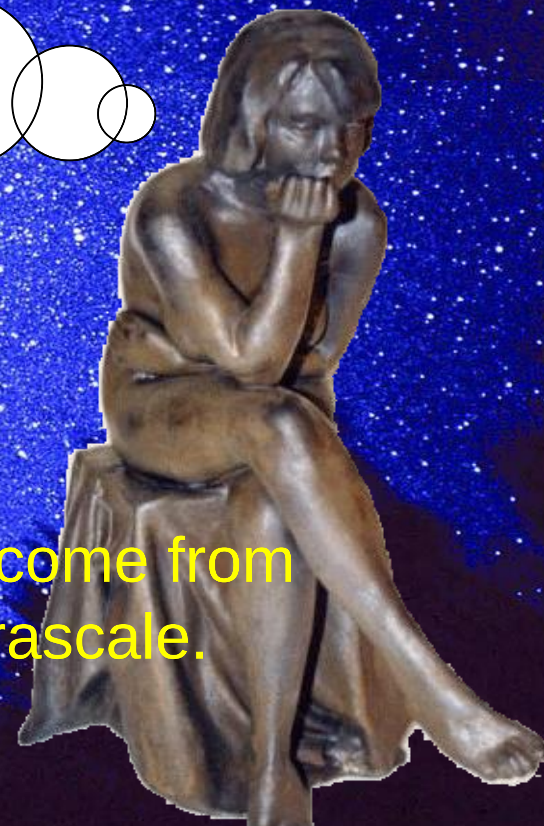




1. Are there undiscovered principles of nature: New symmetries, new physical laws?
2. How can we solve the mystery of dark energy?
3. Are there extra dimensions of space?
4. Do all the forces become one?
5. Why are there so many kinds of particles?
6. What is dark matter? How can we make it in the laboratory?
7. What are neutrinos telling us?
8. How did the universe come to be?
9. What happened to the antimatter?
10. What is mass?

"Quantum Universe" and
"Discovering the Quantum Universe"

Evolved Thinker



Discoveries and breakthroughs will likely come from Energy Frontier Accelerators at the Terascale.

End of Lecture I