Experimental Foundation of the Standard Model

Standard Model

For us, in this course, Particle physics = Standard Model (SM)

The Standard Model is (one of) the major intellectual achievements of the humankind.

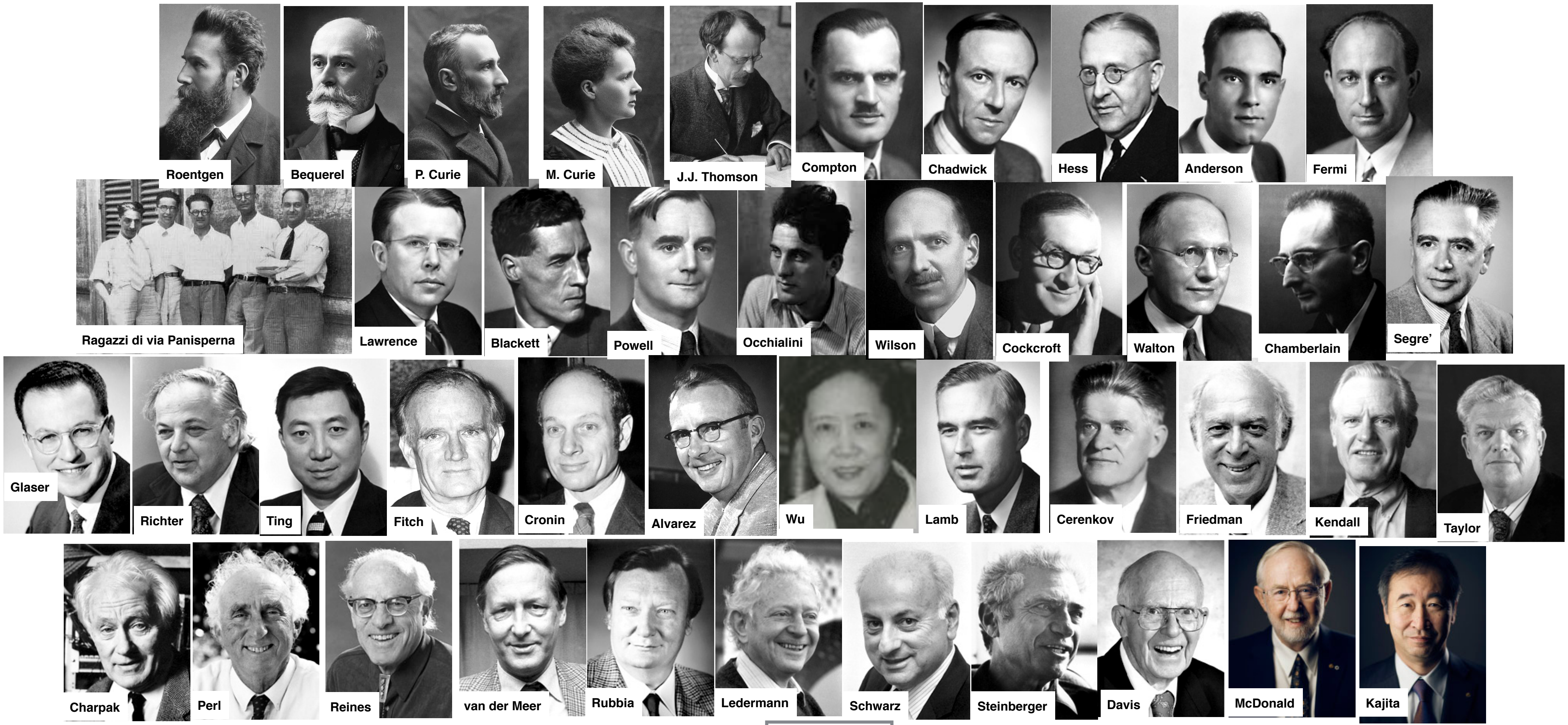
It represents the synthesis of all knowledge we have about the fundamental building blocks of nature and their interactions: i.e. what the stuff is made of and how it works.

It doesn't mean that it is the final word on our knowledge about the universe !
Understanding the SM allows to better understand why we look for BSM and what we measure in HEP. There's still a lot left for you to do !

The SM is the combined outcome of the work carried out over the past century by a very large number of people, both experimentalists and theorists.

Experimental physicist

Experimental physicist invent, build, operate and analyse the data of detectors.
Most of what we will cover in this course comes from these people:



your photo here

Before we start

We want to give a modern view on the foundations of particle physics.
The course will not follow an historical trajectory, still if we look at the material we will discuss we practically place the beginning of our course around the ‘60s

The history of particle physics is fascinating and we encourage all students to read about it!
But this course aims at giving the students working tools to understand the pillars of the SM.
(Keep in mind that the history of the SM is not a pathway of successful great ideas. Textbooks typically don’t show the many false starts, blind alleys and mistakes.)

“The history of an idea is an accident. The only real test in physics is the experiment and the history is fundamentally irrelevant”
R.P.Feynman

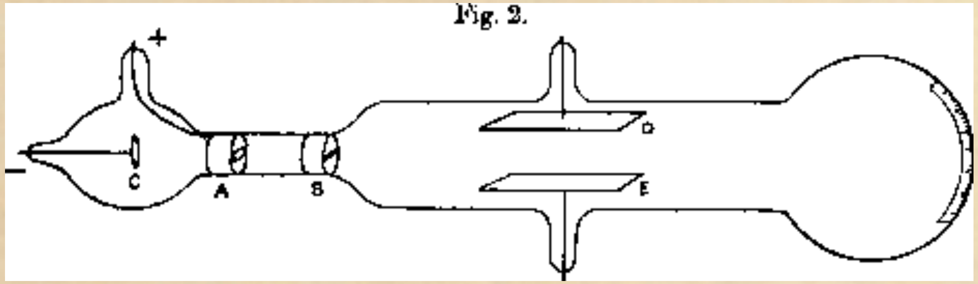
Today is going to be the only “semi-historical lecture” of the course.
It’s just a view of the landscape.

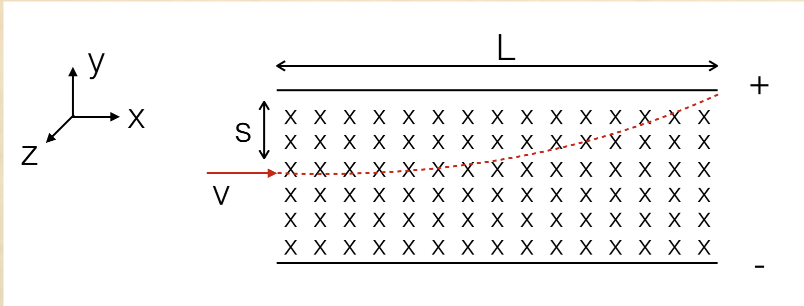
The early days of particle physics

1895 W. Roentgen discovers X-rays <— the time-zero of the SM is clearly arbitrary
1896 H. Bequerel discovers radioactivity in Uranium
1898 M. Curie and P. Curie started the work that lead to the discovery of Radium and Polonium
1898 J.J. Thomson shows that cathode rays are particles: **ELECTRON**

Q: How did he do that ?

Electron discovery





The idea is to compensate the deflection caused by the magnetic field with an electric field

Balancing the forces you get:

$$\frac{e}{m} = \frac{2sE}{L^2B^2} = 1.7588\ 10^{11} Ckg$$

From macroscopic quantities you get the charge to mass ratio of the electron

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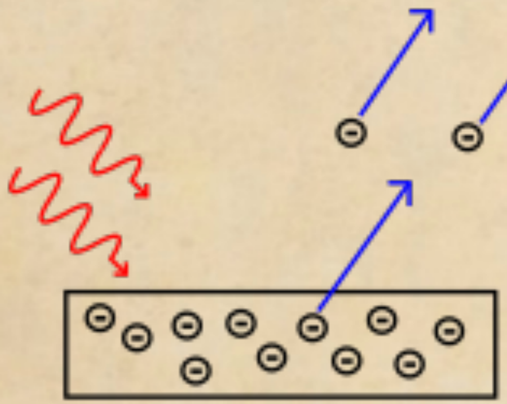
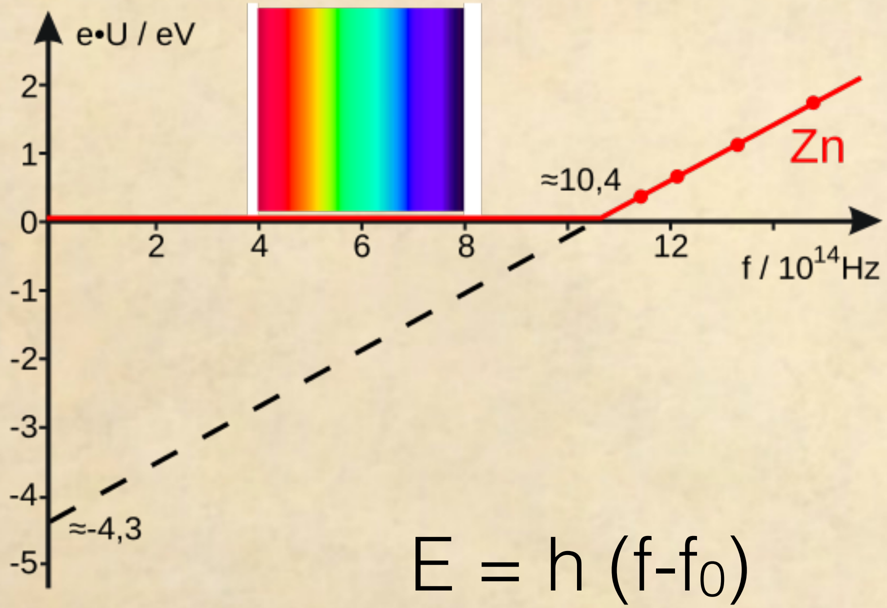
Q: what was his reasoning ?

Photoelectric effect





$$E = h\,(f - f_0)$$

It's a threshold effect in frequency (i.e. energy)
The main point is that the emission is instantaneous !

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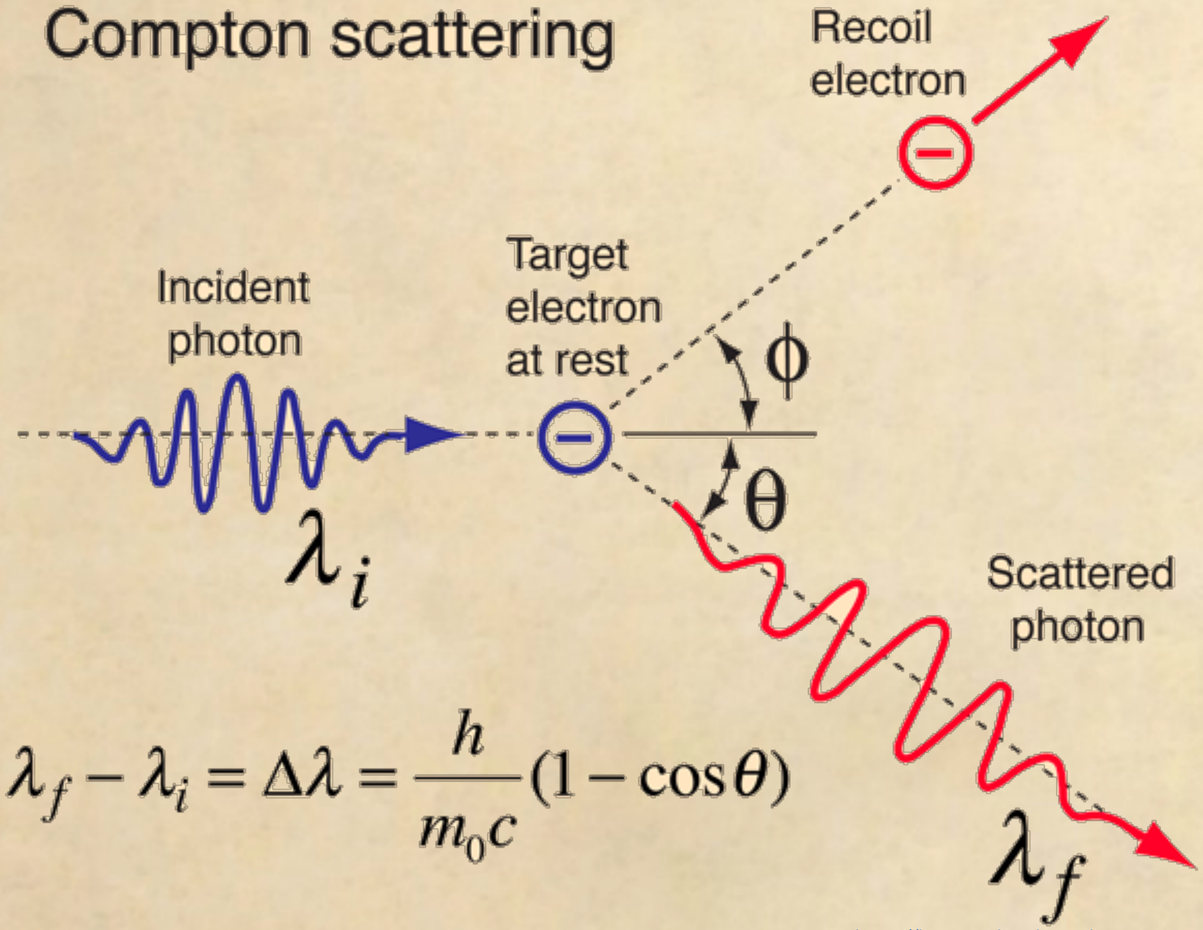
1923 Compton scattering

Q: why is this considered to be the experimental confirmation of the photon hypothesis ?

Compton scattering



$$\lambda_f - \lambda_i = \Delta\lambda = \frac{h}{m_0 c}(1 - \cos\theta)$$

http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/compton.html

Photons and electrons behave as particles and follow Planck and relativistic kinematics.

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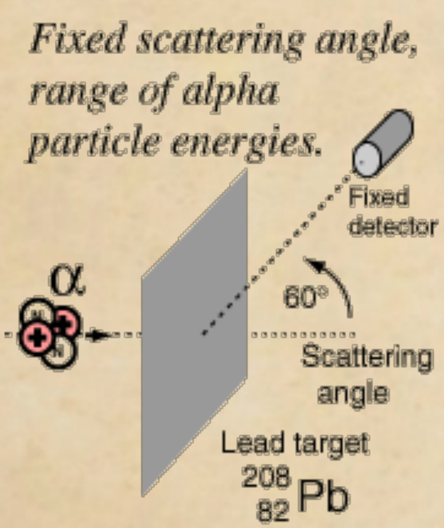
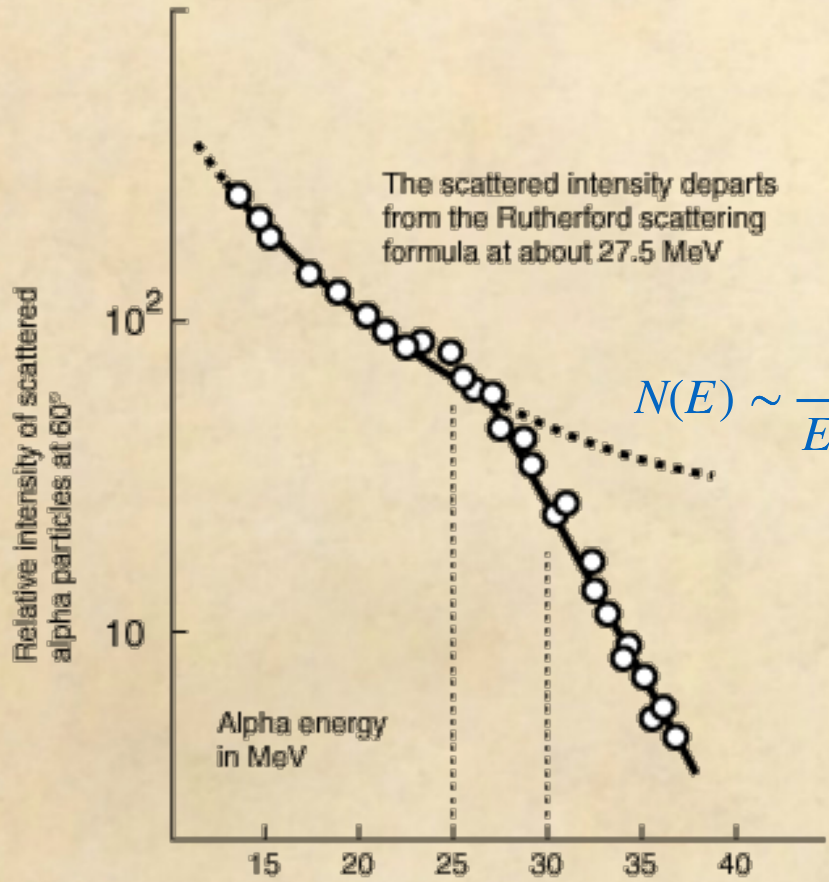
1911 E. Rutherford (Geiger and Marsden) experiment. Birth of **nuclear physics**

Q: Why the Thomson model is not compatible with Rutherford observations ?

Rutherford-Geiger-Mardsen

The probability to backscatter due to multiple scattering is negligibly small.





$$N(E) \sim \frac{1}{E^2 sin^4(\theta/2)}$$

First measurement of the proton radius ~7 fm

"It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you."

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1913 Moseley through X-rays K-lines shows the positive integer charge of the nucleus **PROTON**. Problem of isotopes (same charge but different atomic weights)

Q: What was the understanding of the nucleus composition at this point ?

Moseley X-rays

The order of the elements in the periodic table roughly agrees with the atomic numbers, but there are swaps:
Z = 27 Co = 58.9
Z = 28 Ni = 58.7

Today we understand the nucleus as composed by Z-protons and N number of neutrons (isotopes): A = Z+N

Until Moseley's work, "atomic number" was merely an element's place in the periodic table, and was not known to be associated with any measurable physical quantity. The relation between Z and the X-ray lines he found is:

$$\sqrt{f} = k_1 \cdot (Z - k_2)$$

f = frequency of the X-ray emitted line
k_1, k_2 = spectroscopic constants (K, L, etc… lines)
It's the "proton discovery"

https://en.wikipedia.org/wiki/Moseley%27s_law

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1924-27 Heisenberg, Schroedinger, Dirac, et al. Quantum Mechanics
1932 Chadwick discovers the **NEUTRON**

Neutron discovery

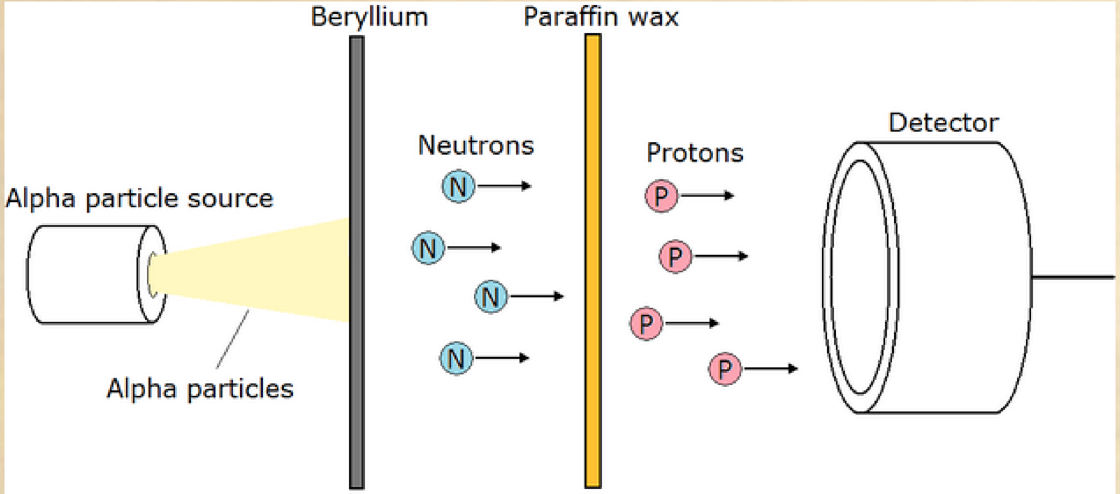

Image from: http://dc.edu.au/hsc-physics-quanta-to-quarks

In 1932 a new, very penetrating, neutral radiation (Y) was discovered bombarding a thin beryllium sheet with α particles:

$$\alpha + Be \rightarrow (\text{new nucleus}) + \gamma$$

γ was initially thought to be high energy photons. Irene Curie and Frederic Joliot studied the scattering of the γ radiation onto a paraffin target. Paraffin is a wax containing a mixture of hydrocarbon molecules having between twenty and forty carbon atoms and about two times more H atoms; it is a cheap way to get a source of protons. They observed the reaction:

$$\gamma + p \rightarrow \gamma + p$$

and measured a mean proton energy of 5.7 MeV. Chadwick proved that the neutral γ radiation could not possibly be high energy photons. By using simple energy momentum conservation a massless photon should have had an energy of ~50 MeV.
Much too high for the available energies of the alpha particles.
The new radiation was due to a neutral massive particle: the neutron

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The modern view of the atom is complete. …the rest is chemistry

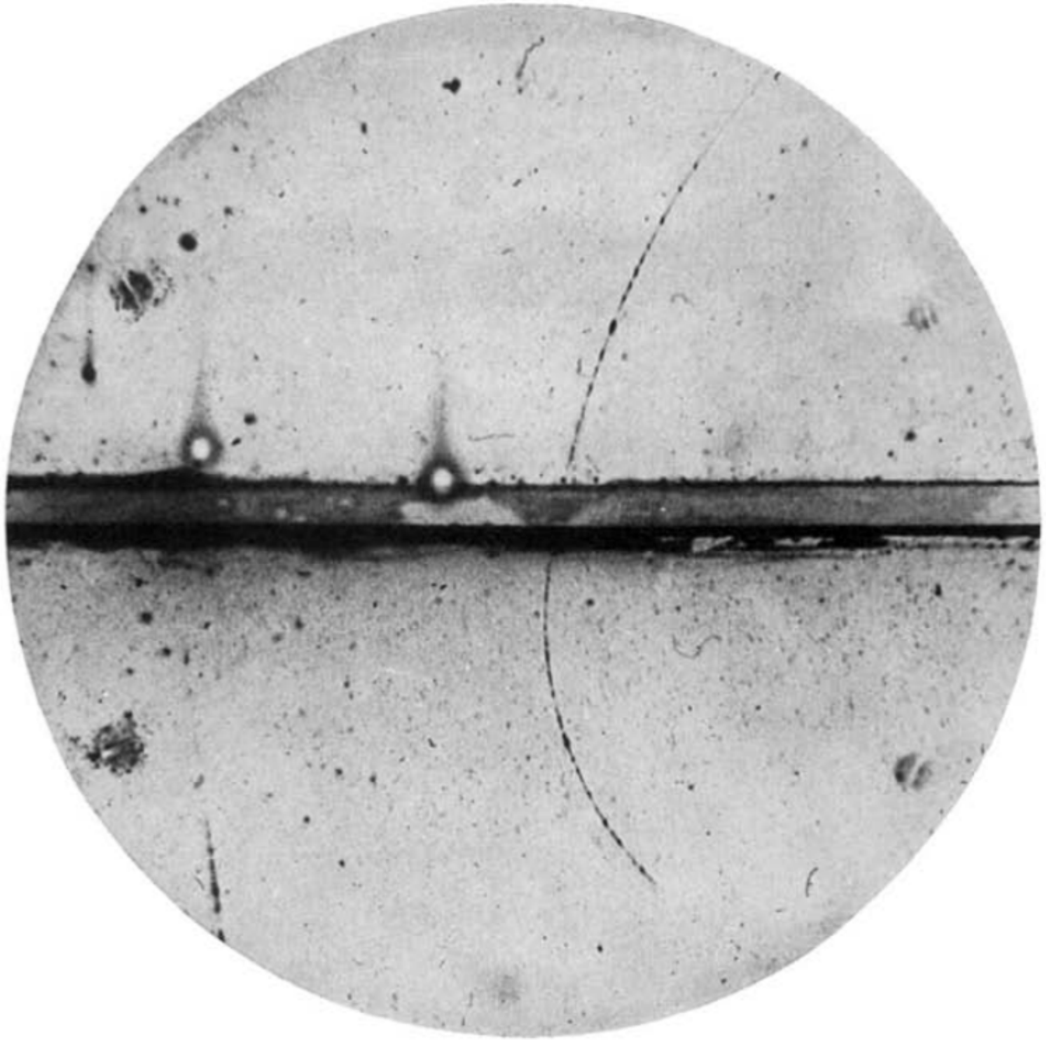
The old days of particle physics

1928 P. Dirac writes his relativistic wave equation: spin and prediction of antimatter

Laboratory particle sources limited in energy:
X-rays and radioactive α, β, γ sources

1911 (D. Pacini) Hess discovers cosmic rays
1932 Anderson discovers the positron in cosmic rays

Positron discovery with a cloud chamber



Old days

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Laboratory particle sources limited in energy:
X-rays and radioactive (alpha,beta, gamma) sources

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All the ingredients of QED are there: e+ e- photon (γ)
Basic processes can be calculated with Dirac's theory:
e-e- —>e-e-, e+e- —> e+e-, γe —> γe

QED: (Stueckelberg) Feynman, Schwinger, Tomonaga

1947 Lamb shift
(g-2) spin precession measurements electron and muon

1955 Segré, Chamberlain: antiproton discovery

g-2 (April, 2021) https://news.fnal.gov/2021/04/first-results-from-fermilabs-muon-g-2-experiment-strengthen-evidence-of-new-physics/

Antiproton

Doubts on antiprotons existence:
proton magnetic moment is different from Dirac predictions (now we know it's not elementary)
…moreover where are the anti-galaxies ?

Bevatron energy 6.5 GeV chosen to observe p p —> p p p pbar

1955 Segre', Chamberlain, Ypsilantis, Wiegand
challenge control π- bkg: done with TOF with scintillators (+ Cerenkov PID)
Roma group (Amaldi) added an emulsion stack after a copper absorber to check the pbar annihilation energy released

Antiproton

Time-of-flight between S1 and S2
antiproton ~ 51 ns
negative pion ~ 40 ns

(Cerenkov counters for xcheck)

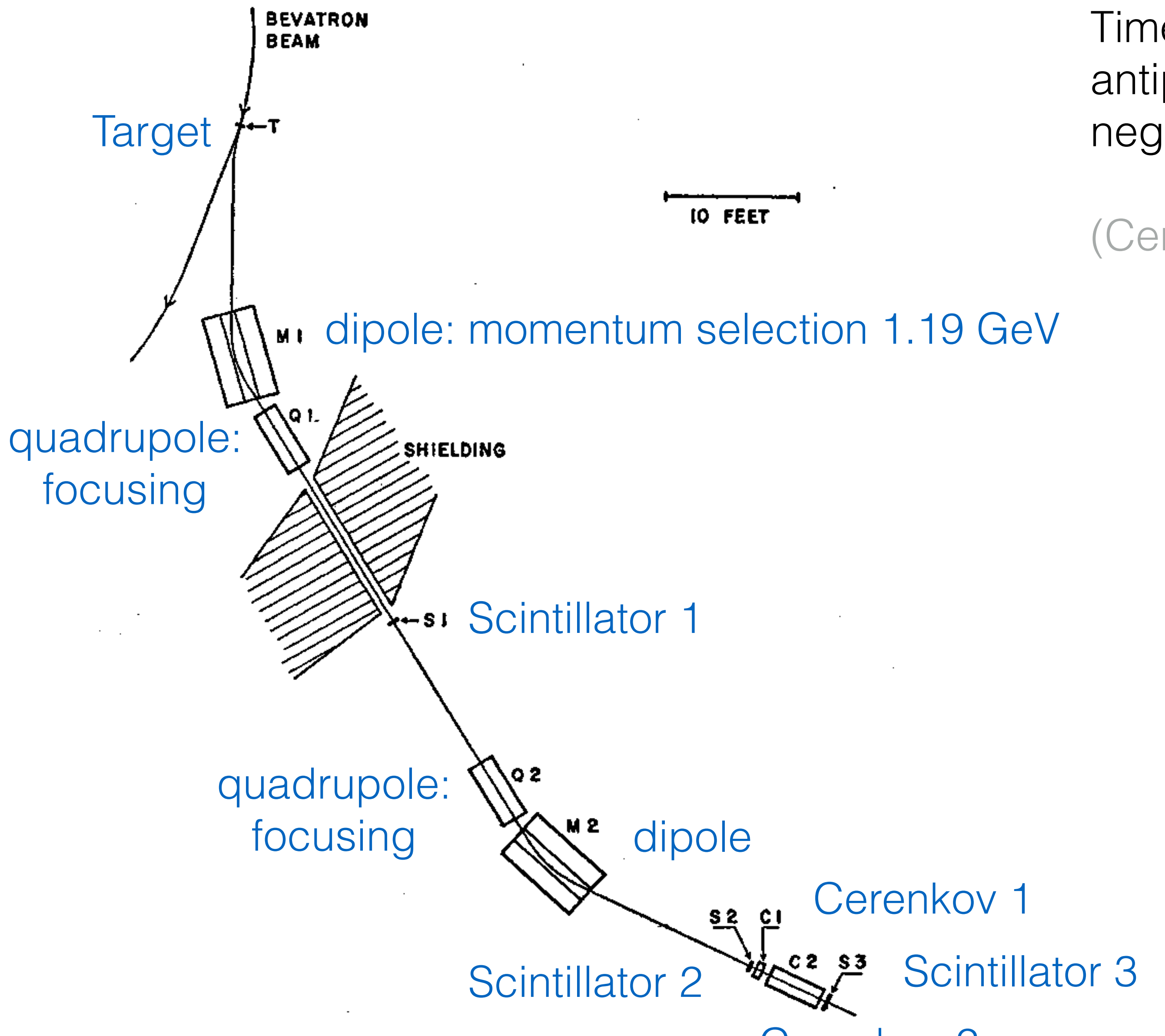
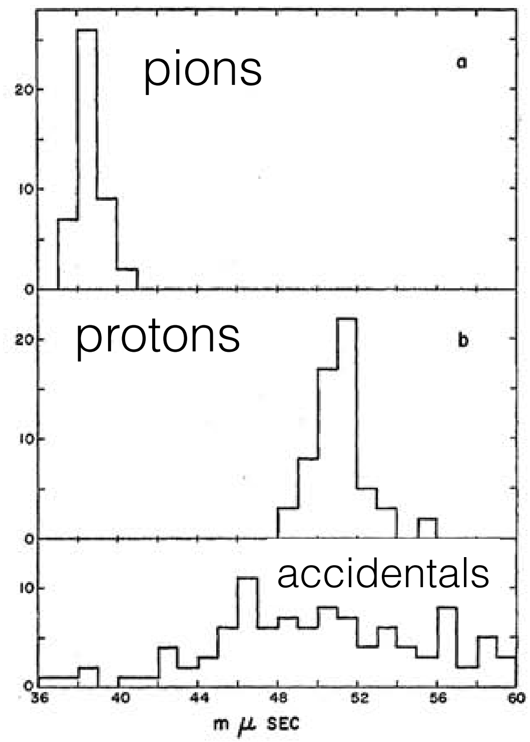
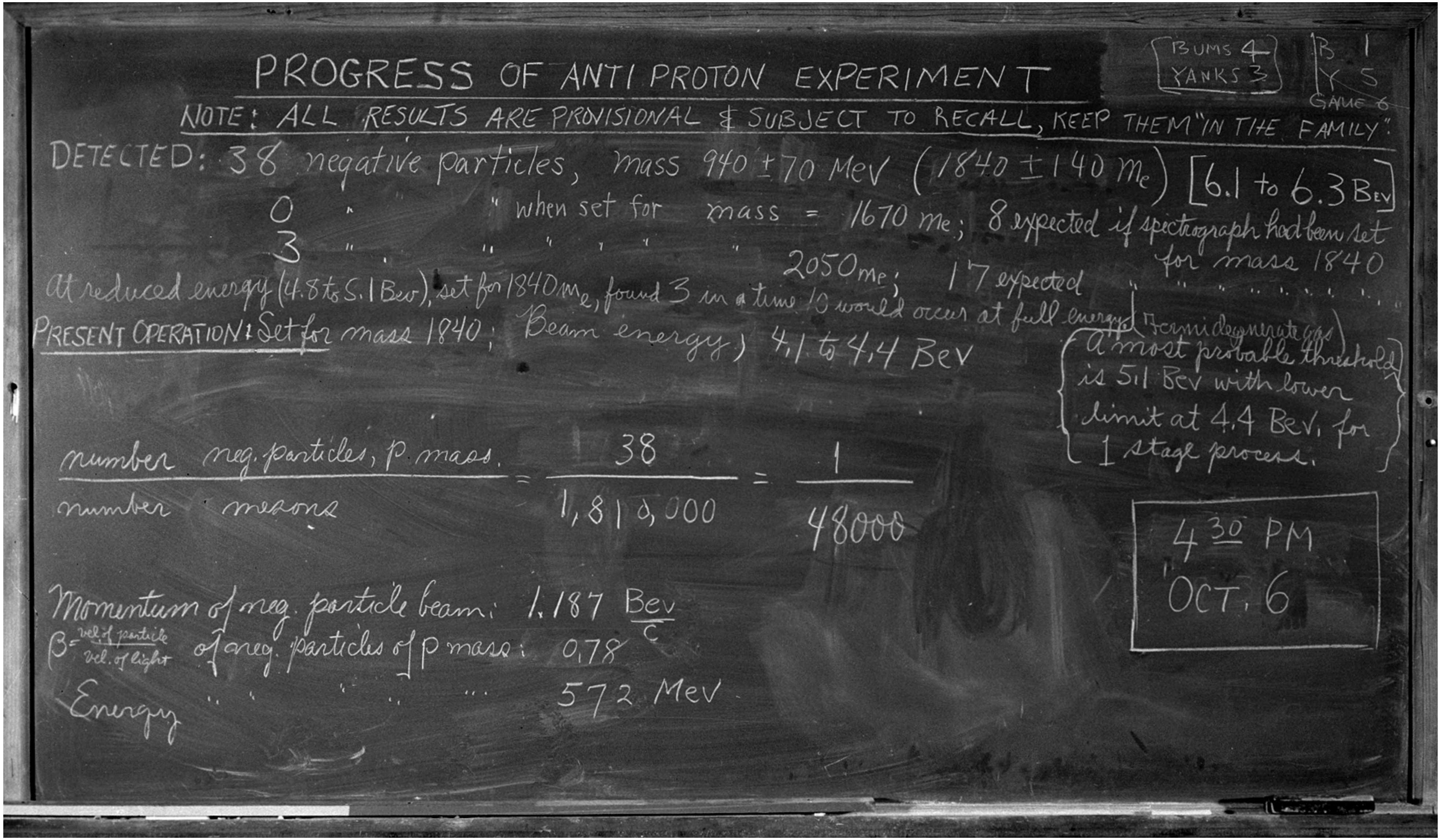


FIG. 1. Diagram of experimental arrangement. For details see Table I.



Antiproton



Wiegand

Antiproton

Mass of the anti-proton verified with emulsions

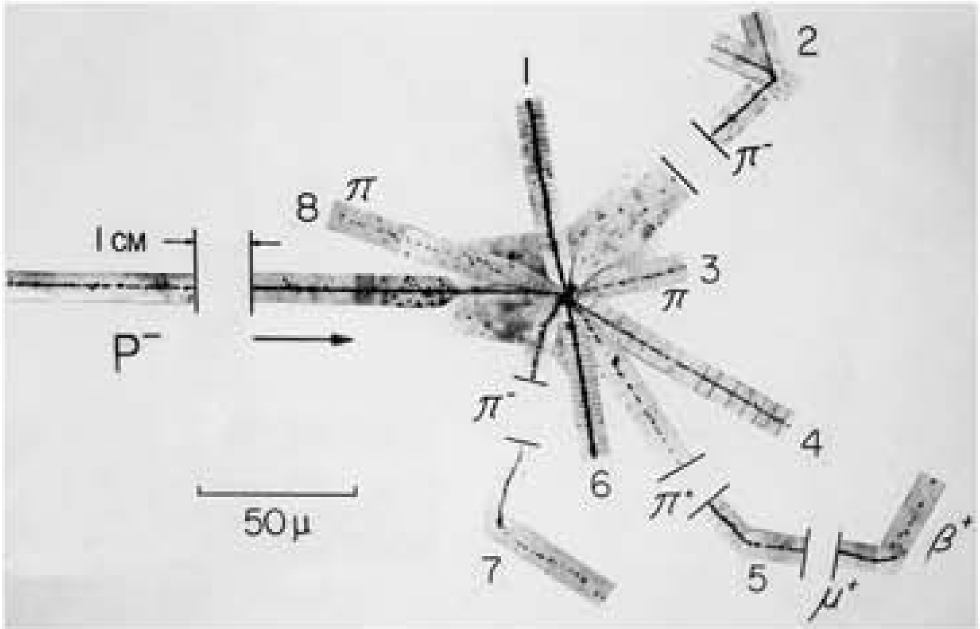


Fig. 2. Reproduction of the P^- star. The description of the prongs is given in Table II. The star was observed by A. G. Ekspong and the photomicrograph was made by D. H. Kouns.

Table II. Measurements and data on the eight prongs of the P^- star shown in Fig. 2.

Track number	Range mm	Number of plates traversed	Dip angle	Projected angle	$p\beta$ Mev/c	Ionization g/g_0	Identity	E_{kin} Mev	Total energy Mev
1	0.59	2	−56.5°	103°			p(?)	10	18
2	27.9	11	+6.5°	61.5°			π^-	43	183
3	>50	81	−73.5°	14.5°	250±45	1.10±0.04	π(?)	174±40	314±40
4	>14.2	16	+53°	318.5°			p(?)	70±5	78±5
5	6.2	3	+4°	305.5°			π^+	30±6	170±6
6	9.5	15	−63.5°	281°			T(?)	82	98
7	18.6	30	−83.5°	255°			π^-	34	174
8	>22.3	16	+33°	163°	190±30	~1	π(?)	125±25	265±25

Total visible energy[a]: 1300±50 Mev
For momentum balance: ≥100 Mev
Total energy release: ≥1400±50 Mev

QFT - QED

Quantum Field Theory is the framework in which the Standard Model is built.
We will not develop, not do any calculation in QFT in this class, but we will use some results

QFT is more than a relativistic formulation of quantum mechanics.

The fundamental objects are the fields.
All particles of the same type are IDENTICAL —> Particles are excitations of the fields.
Every type of particle comes from its own field (electron field, muon field, etc…) and also forces are understood as interactions of fields (the e.m. field —> photon, etc…)

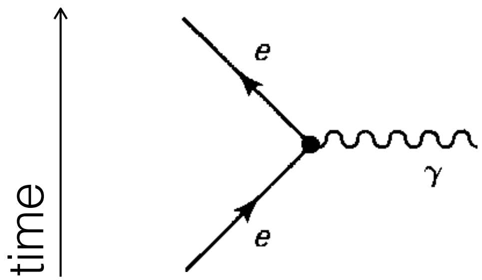
QFT ⊃ GAUGE theories ⊃ SM

Gauge theories are a particular kind of QFT (automatically renormalizable -Veltman, 't Hooft) where the symmetries of the theory dictate the structure of the interactions. (we will see later in the course a simple example)

QFT - QED

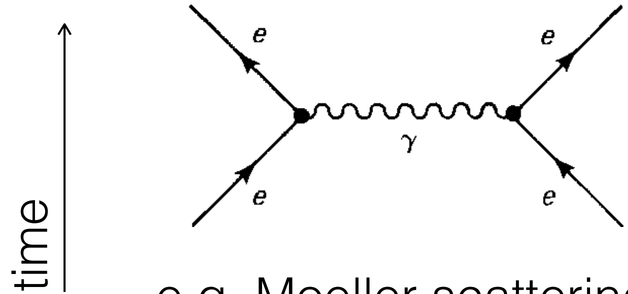
Here we use Feynman diagrams in a qualitative way just to introduce in a pictorial way how particles interact; no need to worry about their mathematical meaning yet.
Let's use QED to see what they are, later we'll see Strong and Weak interactions.
(Just keep in mind they are powerful tools to compute observables from QFT. We will give an idea on how to use Feynman diagrams later in the course. For the derivation of Feynman's rules —> see QFT-1)

All electromagnetic phenomena can be described by this elementary process:

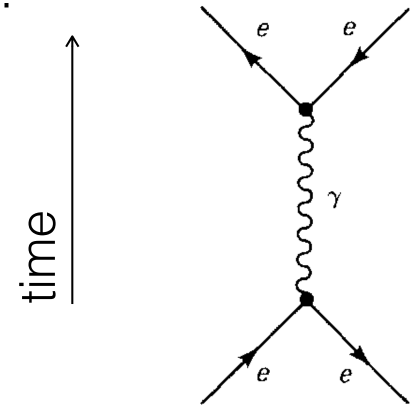


In QFT slang this is called a vertex

Physical processes are described using vertices as building blocks.
Photons are the mediators of the e.m. field.



e.g. Moeller scattering
(Coulomb repulsion)



Particles going back in time are interpreted as anti-particles

QFT - QED

Q: can picture the Feynman diagram corresponding to ?

e+e- —> e+e-

γe- —> γe-

γ γ —> γ γ

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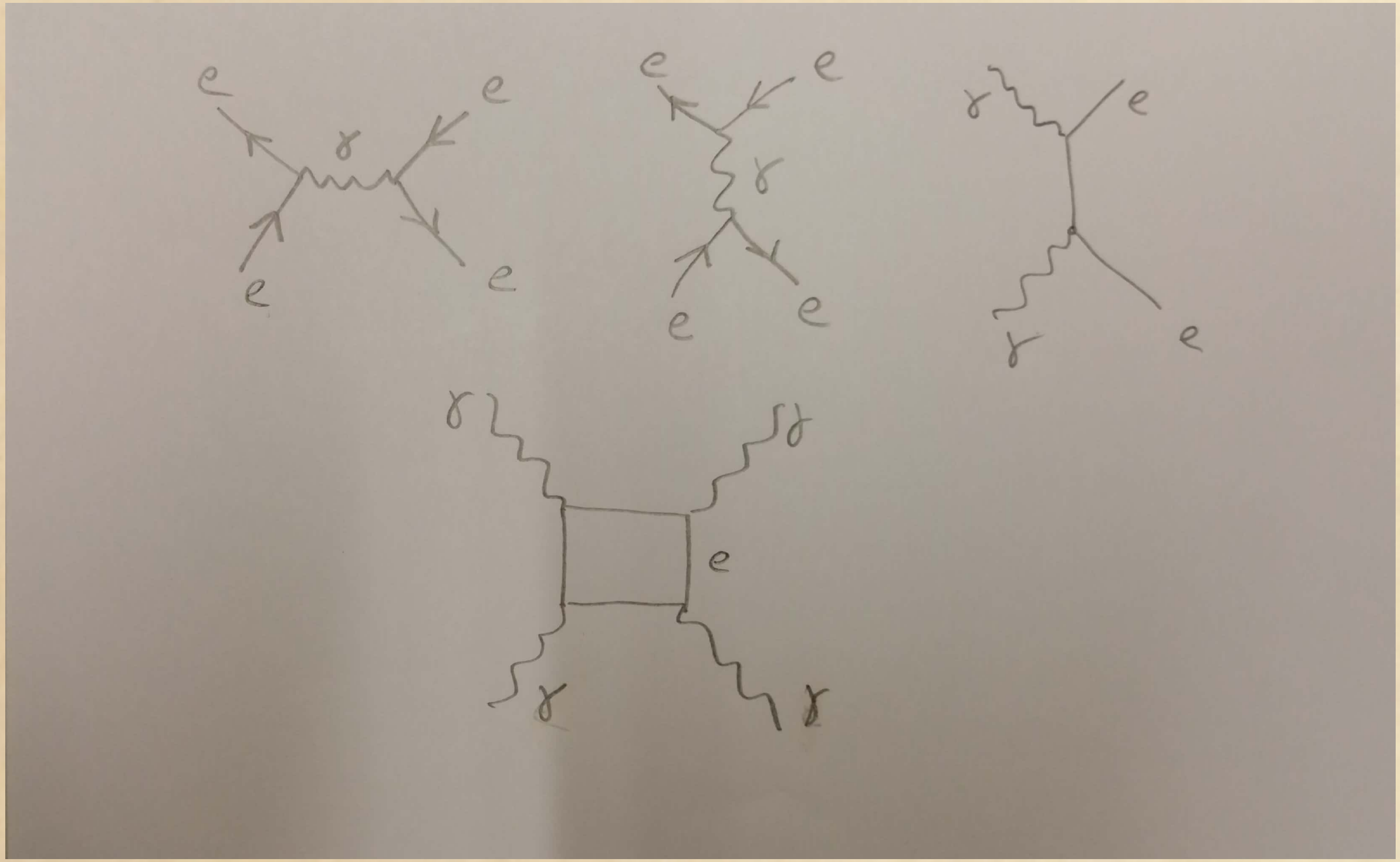
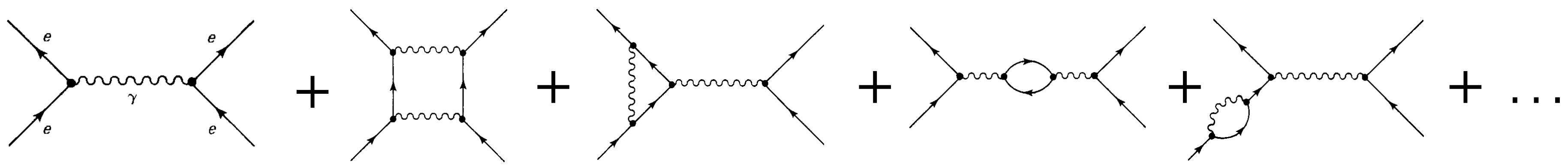


QFT - QED

A typical computation with Feynman diagrams proceeds as follow:

- Draw all possible diagrams with the external lines corresponding to the process. The internal lines are not observable ! they are called virtual particles (we'll see later what virtual means)
- Apply Feynman rules and compute the desired observable (e.g. cross section):
    - transform the diagrams in actual QFT expressions
    - sum the amplitudes from all diagrams

$$\sigma = \Bigg|$$



$$\Bigg|^2$$

(this series is a perturbative expansion).
Each vertex enters the expression with a factor α=1/137 (the fine structure constant), so diagrams with more and more vertices will contribute less and less.

QED is the most numerically precise theory we have !

Pion muon and neutrino

1933 Pauli postulates the existence of the neutrino from beta-decays electron E-spectrum
$n \longrightarrow p\ e^-$ neutrino

Q: What's the problem Pauli wanted to solve by postulating the existence of a neutrino ?

Pion muon and neutrino

Q: What's the problem Pauli wanted to solve by postulating the existence of a neutrino ?

2 body decays gives mono-energy particles
>=3 body decays gives a continuum spectrum

Bohr proposed that the energy was not conserved at microscopic scale

Pion muon and neutrino

1933 Pauli postulates the existence of the neutrino from beta-decays electron E-spectrum
Fermi provides a quantitative theory for the n—>p e nu decay
1934 Yukawa: propose a theory with a mediator equivalent to the photon for strong interaction
1937 mesotron (muon) discovery Anderson and Neddermeyer, and independently by Street and Stevenson

Anderson Neddermeyer, while measuring the energy loss by cosmic radiation, found a particle heavier than the electron but much lighter than a proton which didn't ionize much (i.e. more penetrating)

Today we call it "muon" (μ) and it's the first elementary unstable particle discovered.

It's appearance was initially very confusing. It was thought to be Yukawa meson, carrier of the strong force.

1940 Tomonaga-Araki: predict that negative/positive mesons have different behaviours in matter. Negative: form tight bound state, capture by the nucleus because it's the carrier of the nuclear force. Positive come to rest in matter and decay.

1947: muon identified as a lepton by Conversi, Pancini and Piccioni (Rome)

Q: how would you set up an experiment to check that the muon is not the carrier of the strong interaction?

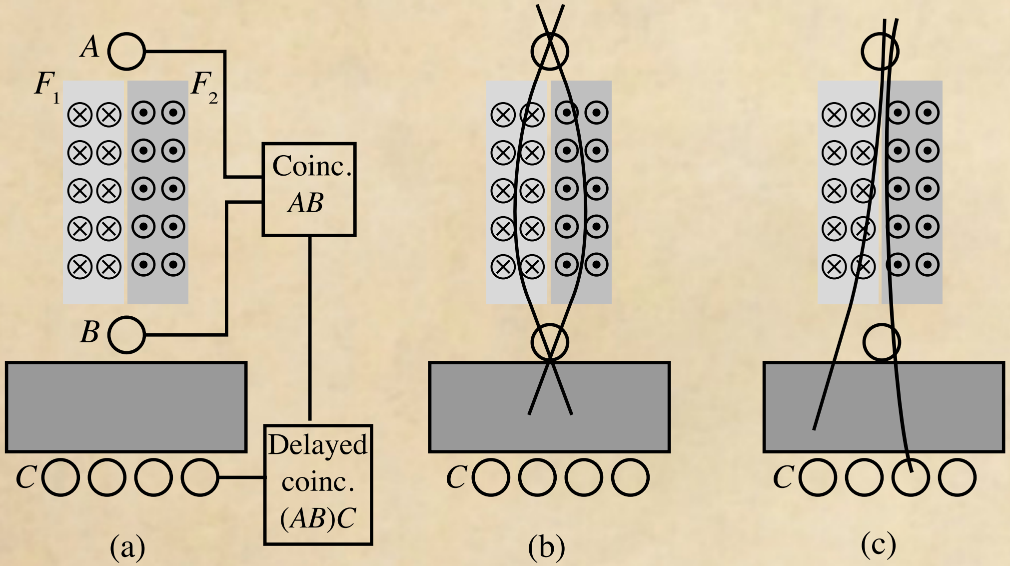
Conversi Pancini Piccioni

If the mesotron carries the strong force it should interact immediately with nuclei

The experiment aimed at investigating whether the absorption of positive and negative particles in a material was the same or different. Actually, a negative particle can be captured by a nucleus and, if it is the quantum of nuclear forces, quickly interacts with it rather than decaying. In contrast, a positive particle is repelled by a nucleus and will decay as in vacuum.

The two iron blocks, F_1 and F_2 in the upper part of Fig. 2.1, are magnetised in opposite directions normal to the drawing and are used to focus the particles of one sign or, inverting their positions, the other. The ‘trigger logic’ of the experiment is the following. The Geiger counters A and B, above and below the magnetised blocks, must discharge at the same instant (‘fast’ coincidence); one of the C counters under the absorber must fire not immediately but later, after a delay Dt in the range 1 us < Dt < 4.5 us (‘delayed’ coincidence). This logic guarantees the following: first that the energy of the particle is large enough to cross the blocks and small enough to stop in the absorber; second that, in this energy range and with the chosen geometry, only particles of one sign can hit both A and B; and finally that the particle decays in a time compatible with the lifetime value of Rossi and Nereson.

A. Bettini Ch.2



(a) setup; b) shows the trajectory of two particles of the ‘right’ sign in the right energy range, which discharges A and B but not C; Fig. 2.1(c) shows two particles of the ‘wrong’ sign. Neither of them gives a trigger signal because one discharges A and not B, the other discharges both but also C. In a first experiment in 1945, the authors used an iron absorber. The result was that the positive particles decay as in vacuum, the negative particles do not decay, exactly as expected.

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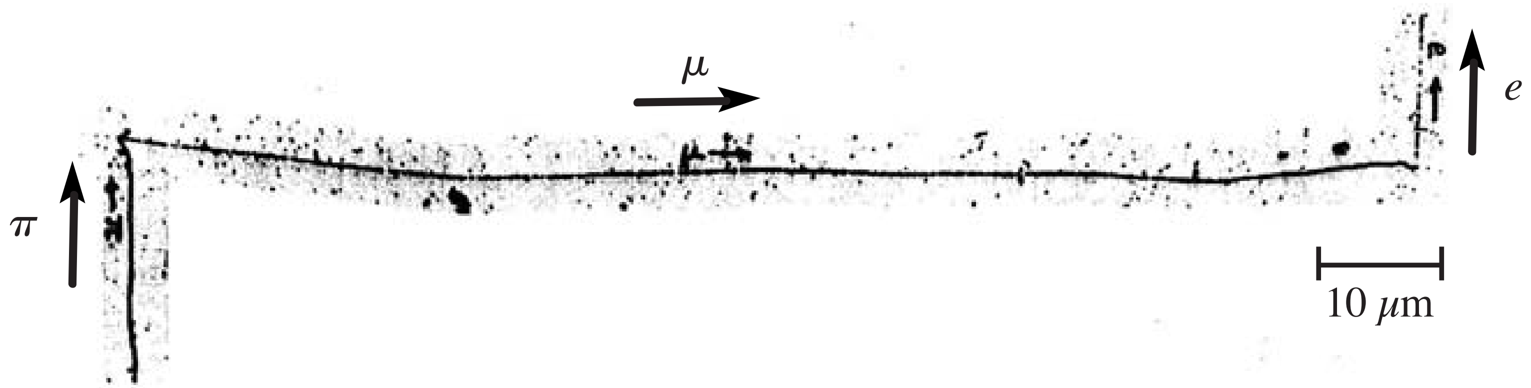
1947: Occhialini/Powell discover the pion —> and this is the Yukawa meson !



Q: what are the kinks due to ?
Q: in the second kink, how do you know they are 2 neutrinos and not one ?

Pion muon and neutrino

Q: what are the kinks due to?

They signal the presence of at least one invisible particle: the neutrino

Q: how do you know they are 2 neutrinos and not one ?

By measuring the energy spectrum of the charged particles.
If mono-energetic 1 if spectrum more than 1

Pion muon and neutrino

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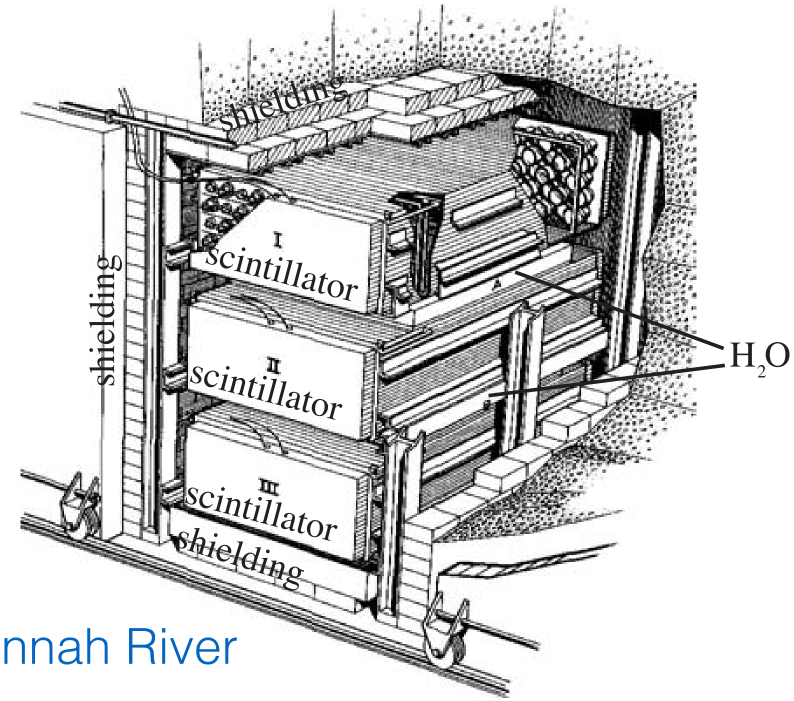
1947: Occhialini/Powell discover the pion —> and this is the Yukawa meson !
1955 Cowan and Reines finally give the experimental proof of (anti)neutrino existence
(in a sense so far the neutrino was “simply there” it wasn’t doing anything.
Here we see it interacting !)



Savannah River

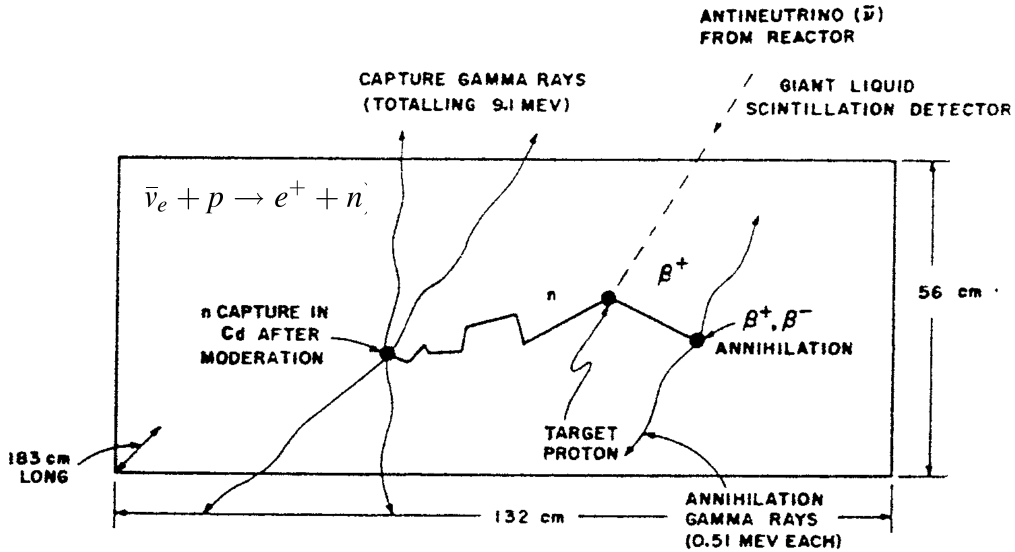


Figure 6.3. A schematic diagram of the experiment of Reines and Cowan in which antineutrinos from a nuclear reactor were detected. The dashed line entering from above indicates the antineutrino. The antineutrino transmutes a proton into a neutron and a positron. The annihilation of the positron produces two prompt gamma rays, which are detected by the scintillator. The neutron is slowed in the scintillator and eventually captured by cadmium, which then also emits delayed gamma rays. The combination of the prompt and delayed gamma rays is the signature of the antineutrino interaction (**Ref.** 6.7).

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Here we see it interacting !)

Q: How would you distinguish a neutrino from an antineutrino ?

Q: Are there different families of neutrino ?
How would you distinguish an electron-neutrino from a muon-antineutrino ?

Life in physics and the crucial sense of wonder
https://cerncourier.com/a/life-in-physics-and-the-crucial-sense-of-wonder/

Pion muon and neutrino

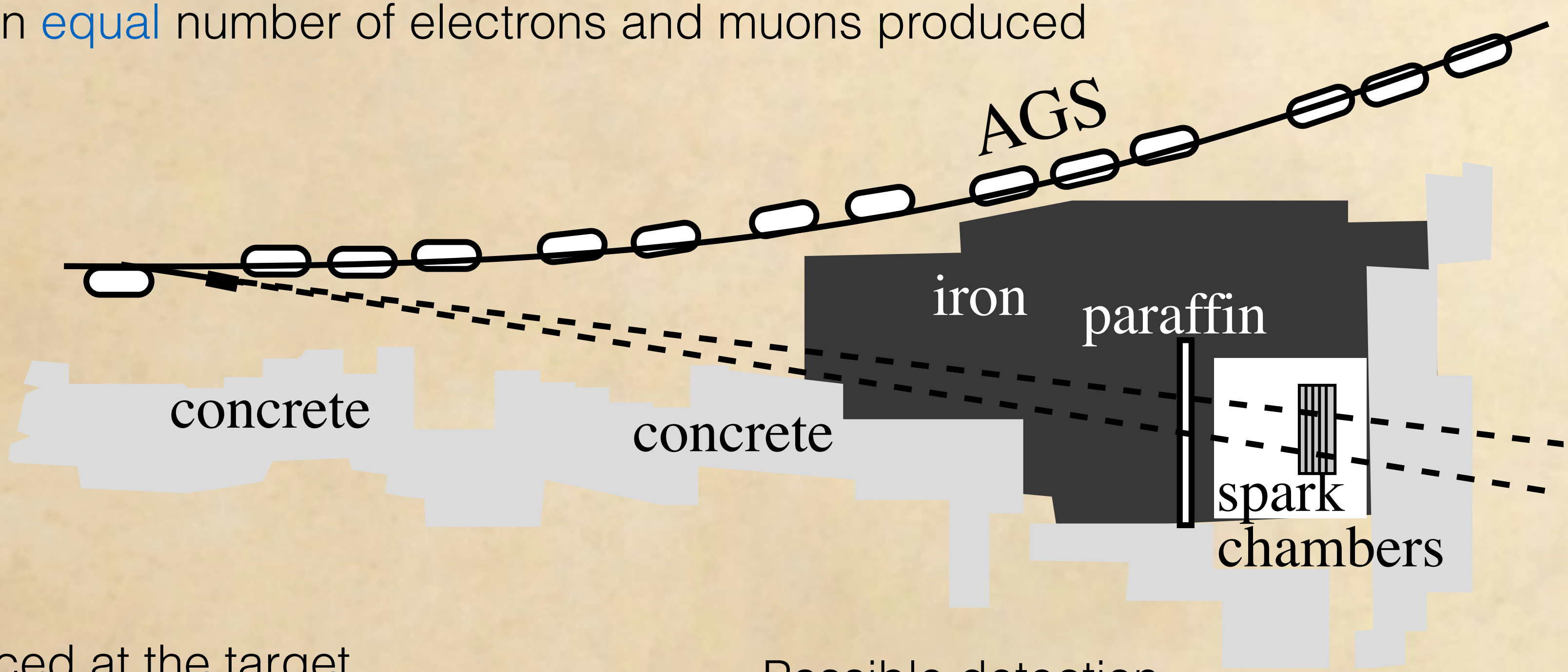
Q: How would you distinguish a neutrino from an antineutrino ?

ν n -> p e- occurs
$\bar{\nu}$ n -> p e- does not occur

Muon neutrino

Q: Are there different families of neutrino ?
How would you distinguish an electron-neutrino from a muon-antineutrino ?

If neutrinos are of one "flavour" when I shoot them on a target I should see an equal number of electrons and muons produced



Produced at the target

$\pi^+ \rightarrow \mu^+ + \nu \qquad \pi^- \rightarrow \mu^- + \bar{\nu}.$

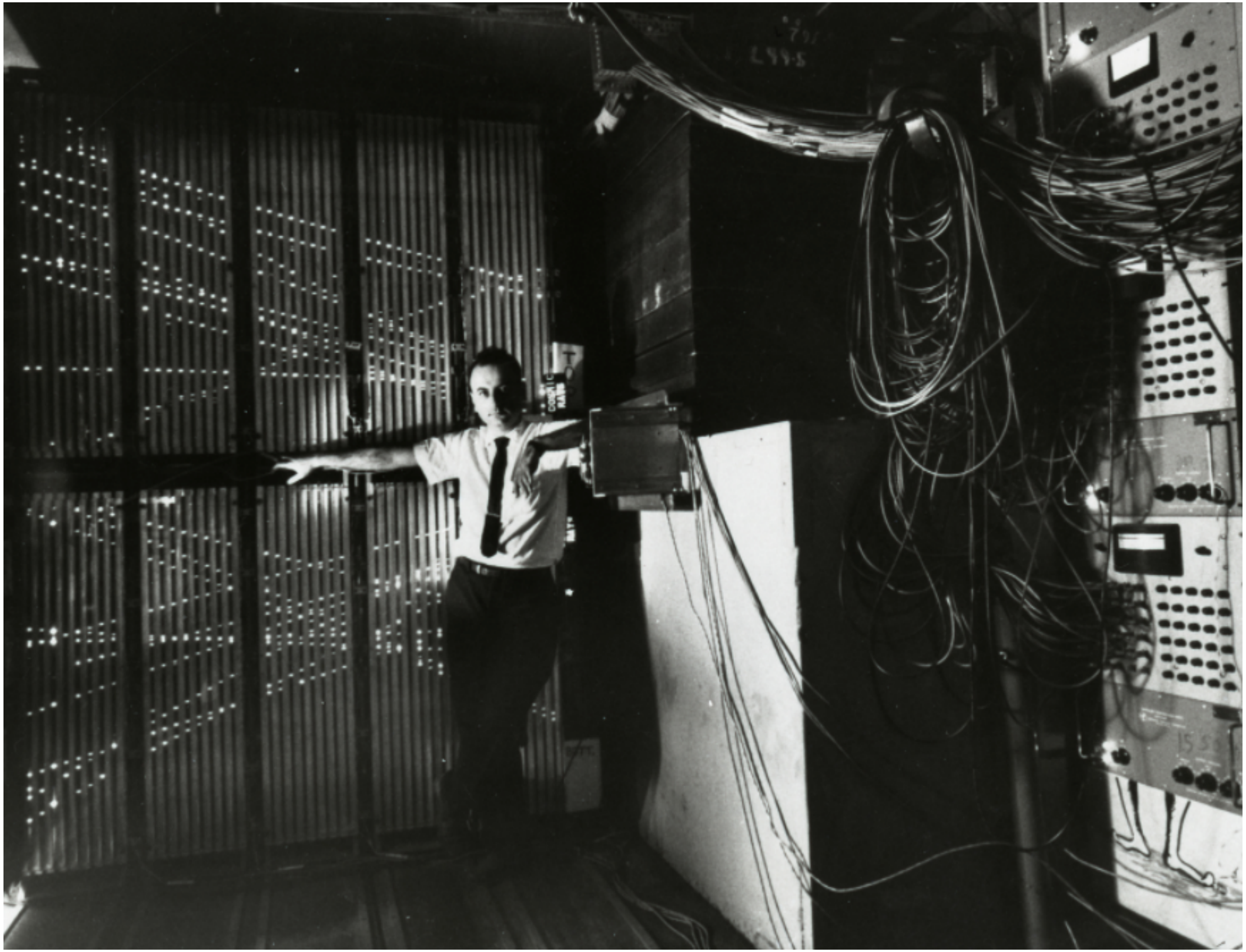
Possible detection

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

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

Only muons seen, no electrons

Spark chambers



Pion muon and neutrino

1933 Pauli postulates the existence of the neutrino from beta-decays electron E-spectrum
Fermi provides a quantitative theory for the n—>p e nu decay
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Lepton number conservation by families:
mu —> e gamma does not occur in the SM
But why we do see mu -> e nu nu, because the 2 neutrinos are different
"electron-ness" and "muon-ness" are conserved —> nu_e nu_mu

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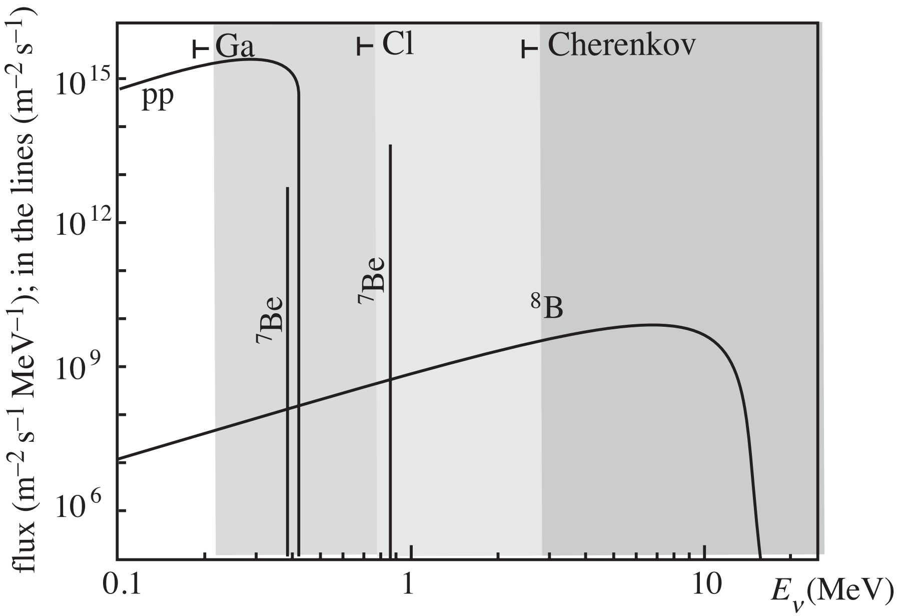
1970-1994 Davis solar neutrino deficit interpreted as neutrino oscillations

Solar neutrino deficit



(b)

$$\nu_e + {}^{37}\text{Cl} \to e^- + {}^{37}\text{Ar}$$

R. Davis used 615 t of perchloroethylene (C_2Cl_4) as the target detector medium, in which about one Ar nucleus per day was expected.

The experiment took place deep underground in the Homestake mine in South Dakota at 1600 m depth

Rate(Cl;,exp) = 2.56 ± 0.16 ± 0.16 SNU
Rate(Cl, SSM)= 8.1 ± 1.3 SNU

~1/3 of the flux is missing

SSM = Solar Standard Model (Bahcall)

Solar Neutrino Units (1 SNU = one capture per 10^{36} atoms per second)

Pion muon and neutrino

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19XX: neutrino and antineutrino interacts differently with matter
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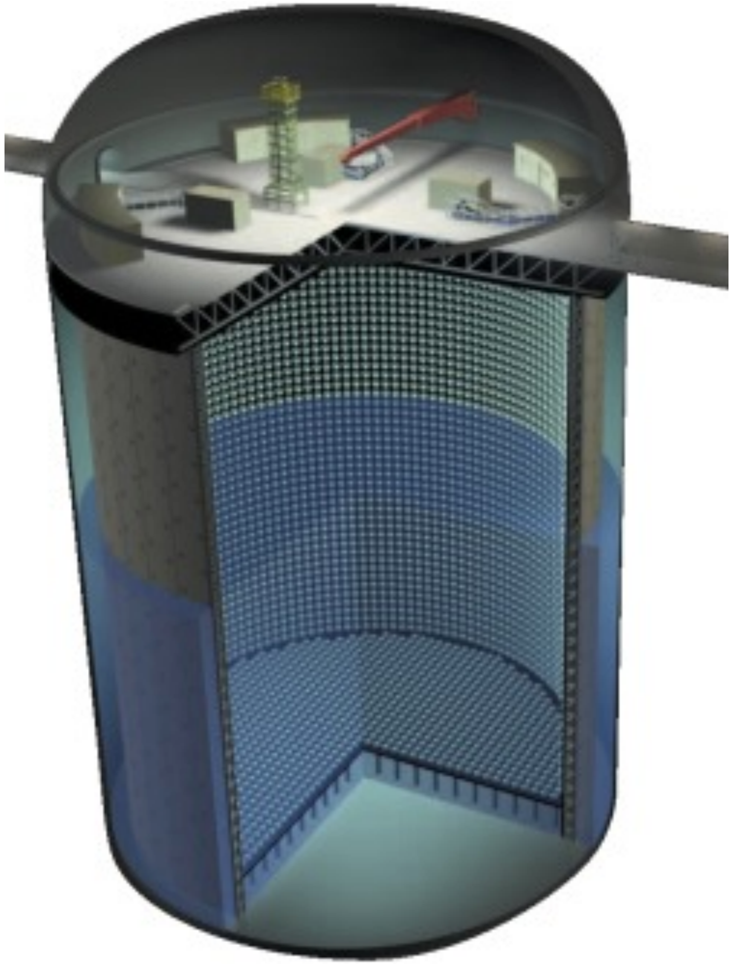
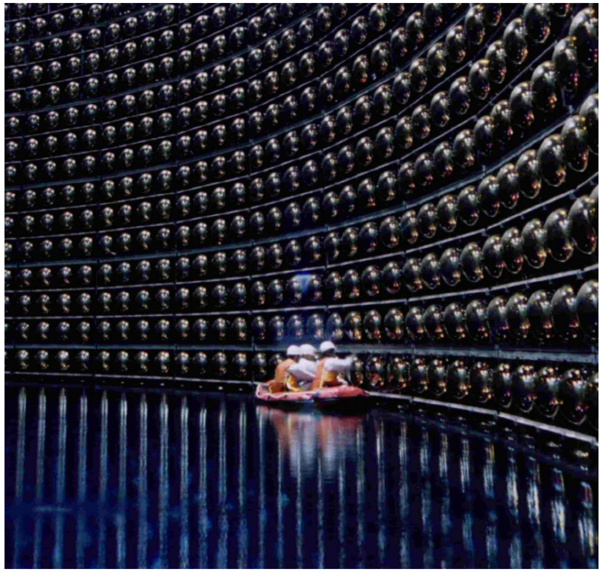
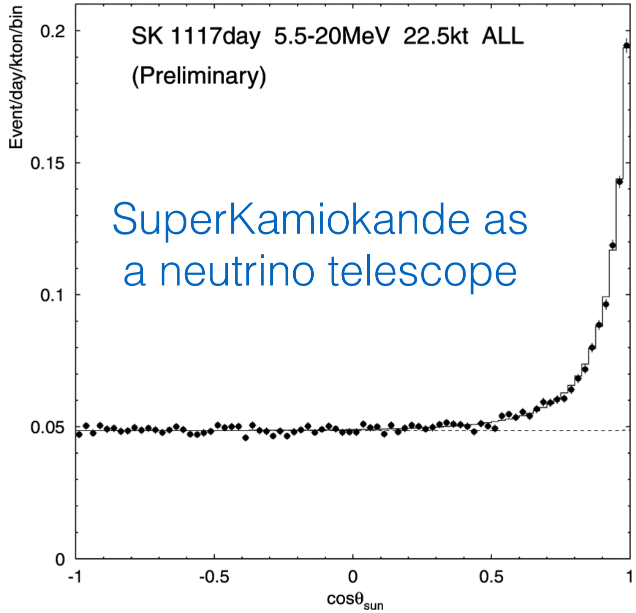
1970-1994 Davis solar neutrino deficit interpreted as neutrino oscillations
1996- : Super-Kamiokande: neutrino oscillations
2000: nu_tau "discovery": DONUT collaboration
1999-2006: SNO total flux nu_e nu_mu nu_tau

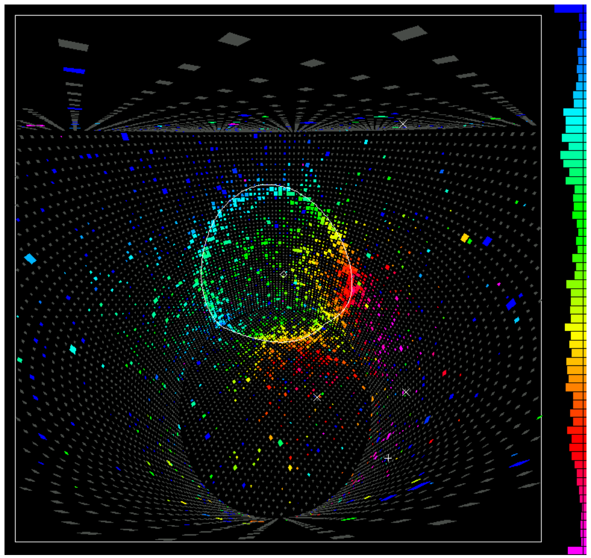
A. Blondel "The third family of neutrinos"
https://arxiv.org/abs/1812.11362

Neutrino oscillations

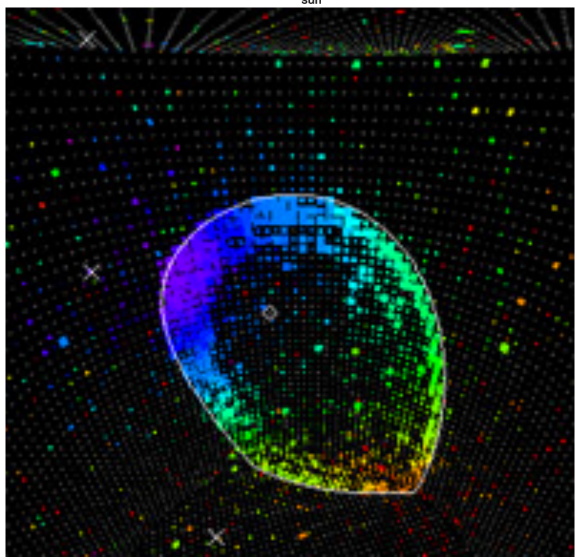








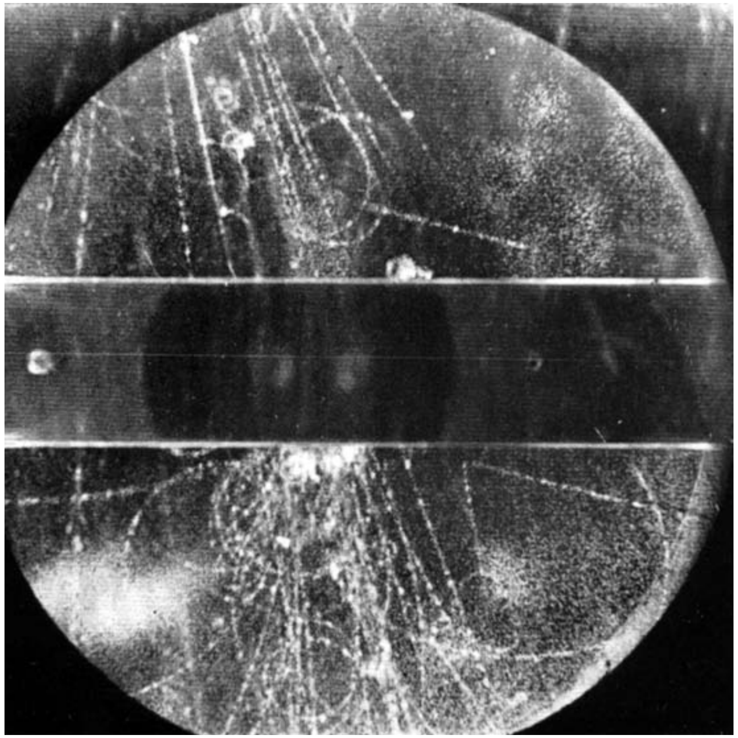
electron neutrino event



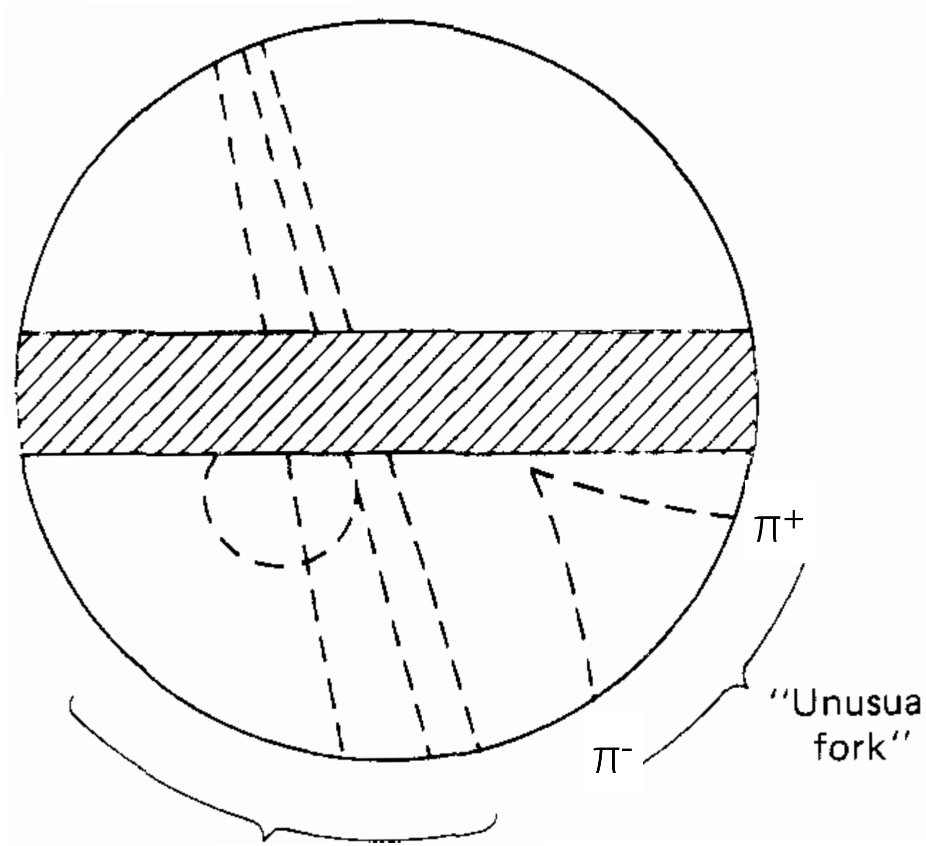
muon neutrino event

Quarks

So far they just knew the existence of pion and muon
More quantum numbers:
1947 V-particles Rochester-Butler (cosmic)
1955 Lambda->p pi- Anderson (cosmics)
Large production cross sections, slow decay (now understood as weak-decay)



Rochester and Butler 1947



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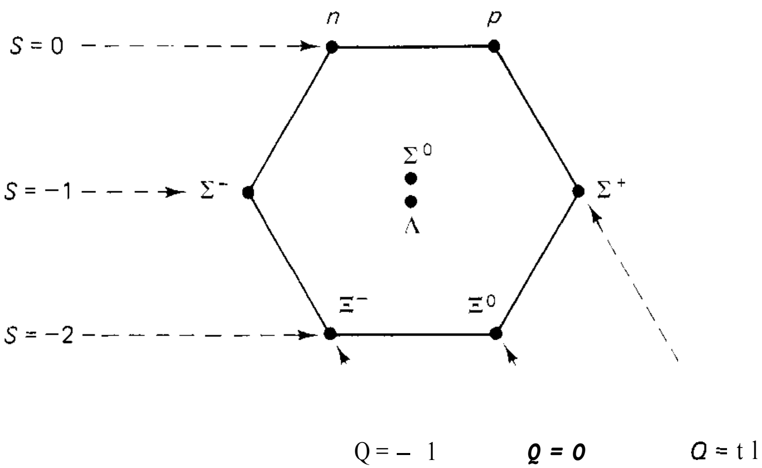
1953 Pais—> Strange particles only produced in pairs
19XX Gell-Mann Nishijima strangeness quantum number (conserved by strong force not by weak)
Strangeness “explains” why some processes occur and why others don’t

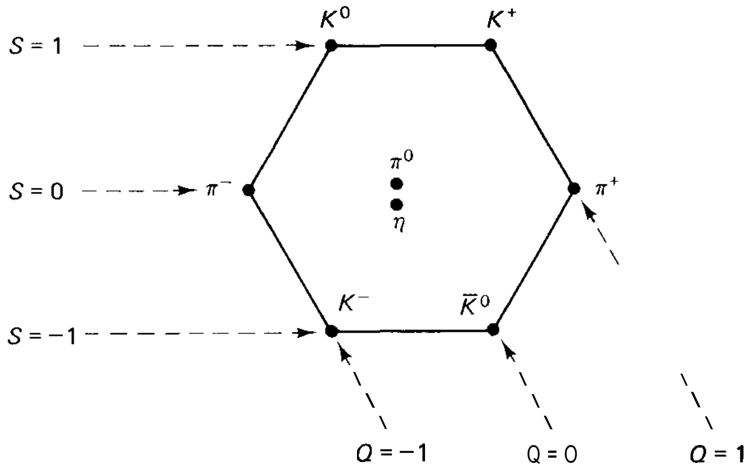
Overabundance of resonance, only classified by mass/charge/strangeness

1961 Eightfold way: Gell-Mann and Ne’eman
1964 Omega- discovery

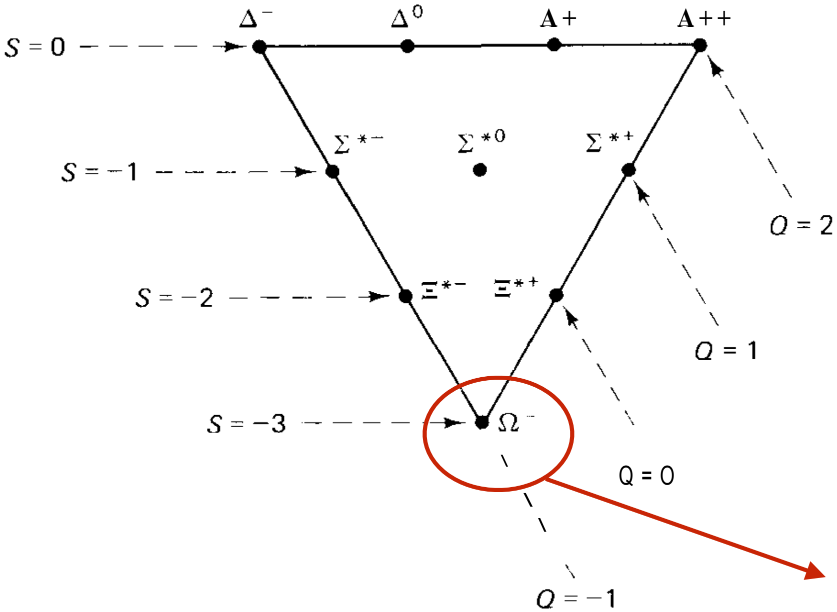
Quarks



The Baryon Octet



The Meson Octet



The Baryon Decuplet

Horizon

“Strangeness Minus Three" (1964)

https://www.youtube.com/watch?v=BGeW6Nc6IMQ

Quarks

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1964 Omega- discovery

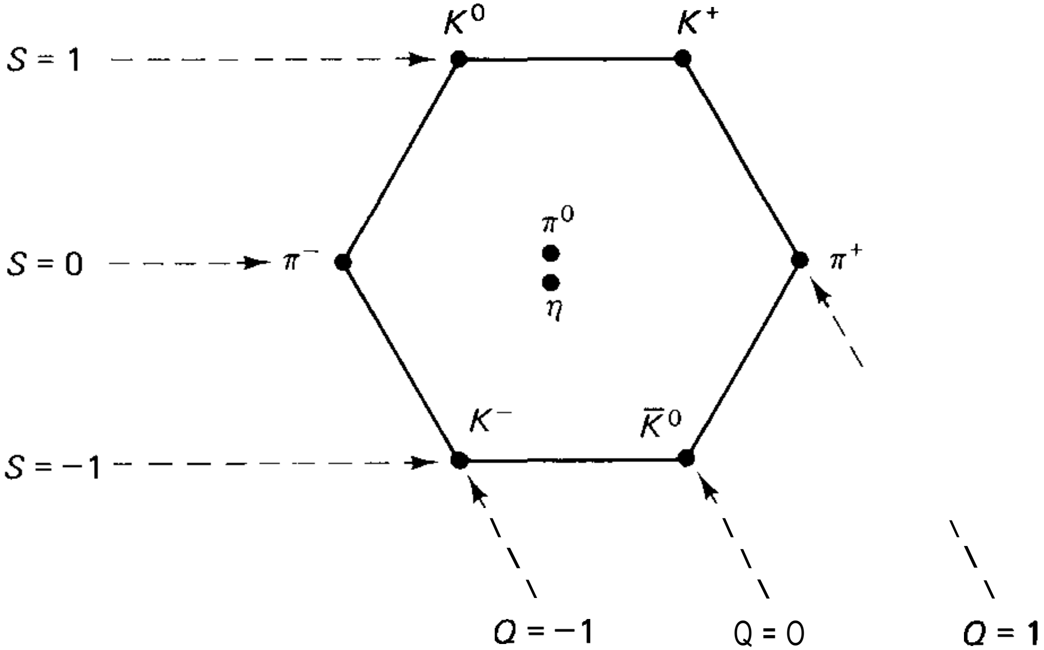
——— "Beginning of modern particle physics" ——— (…again totally arbitrary definition)

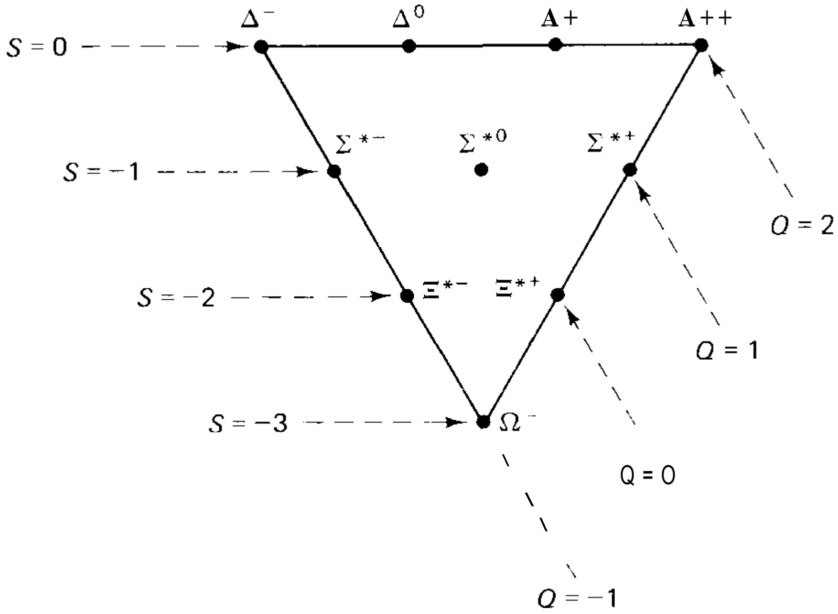
1964 quarks(aces) Gell Mann and Zweig (fermions spin 1/2):
- every baryon is composed of 3 quarks
- every meson is composed of a quark and an anti-quark

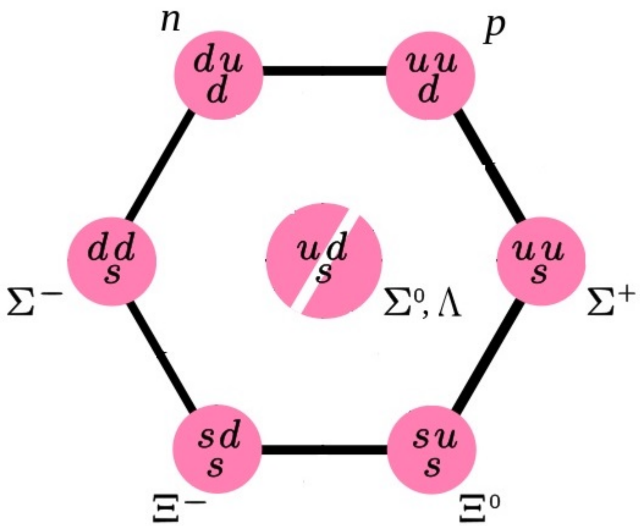
u	q= 2/3
d s	q= -1/3

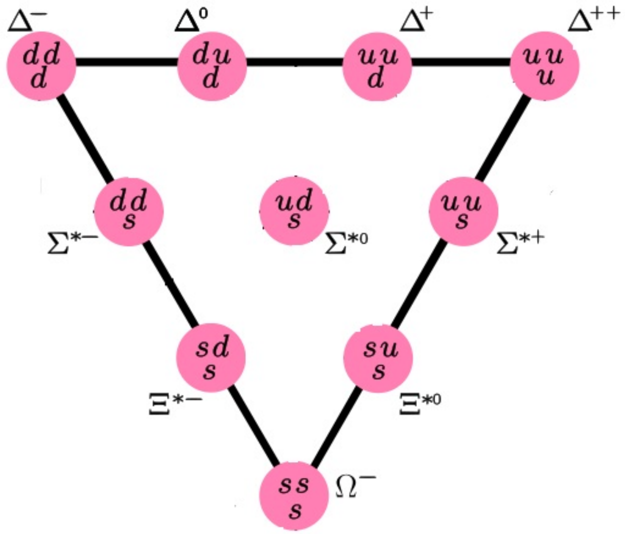
Eight-fold way emerges naturally from the quark model
Different energy states as different particles (H-atom, energy splits o(eV) mass o(GeV))

Quarks


K^0
K^+
$S = 1$
$S = 0$
$S = -1$
π^-
π^0
η
π^+
K^-
$\bar{K}^0$
$Q = -1$
$Q = 0$
$Q = 1$


Δ^-
Δ^0
Δ^+
Δ^{++}
$S = 0$
$S = -1$
$S = -2$
$S = -3$
Σ^{*-}
Σ^{*0}
Σ^{*+}
Ξ^{*-}
Ξ^{*+}
Ω^-
$Q = 2$
$Q = 1$
$Q = 0$
$Q = -1$


n
p
Σ^-
Σ^0, Λ
Σ^+
Ξ^-
Ξ^0


Δ^-
Δ^0
Δ^+
Δ^{++}
Σ^{*-}
Σ^{*0}
Σ^{*+}
Ξ^{*-}
Ξ^{*0}
Ω^-

Quarks

Δ^{++} against Pauli principle: it's a bound state of 3 up-quarks all in the same state (symmetric)
1964 Greenberg proposes a new quantum number: color

The three up quarks do not violate Pauli principle because they come in different colors RGB (antisymmetric)

New principle: All hadrons are color-less and the only combinations that one can make are:

baryons: 3 quarks (RGB) - antibaryons 3 antiquarks ($\bar{R}\bar{B}\bar{G}$)
mesons: quark-antiquark ($R\bar{R}$, $G\bar{G}$, $B\bar{B}$)

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No free quark ever observed.

Q: What is the quark most distinctive property ?
Q: Suppose(as it was in the beginning) you expect they can be "free", what experiment would you setup to detect the presence of quarks ?

Quarks

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Fractional charge: 2/3 -1/3

Q: Suppose(as it was in the beginning) you expect they can be “free”,
what experiment would you setup to detect the presence of quarks ?

“Millikan oil droplets”
They are charged —> from the bending of a track in a magnetic field

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1969 DIS Friedmann, Kendall, Taylor

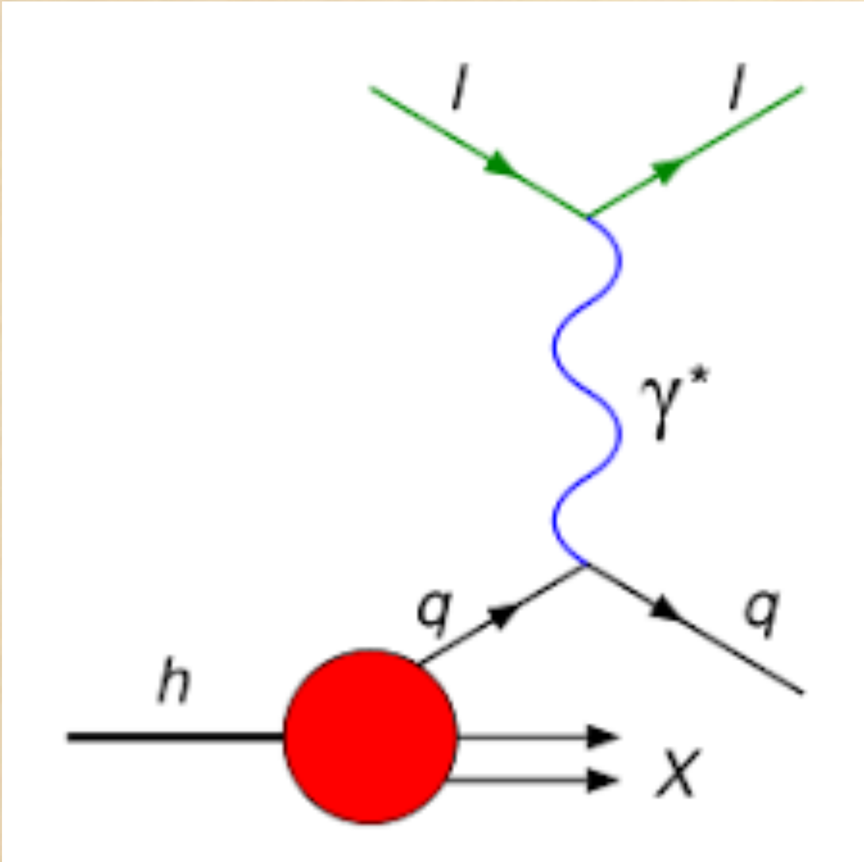
(—> Feynman partons)

Q: How would would you check if the nucleon is elementary ?

Deep Inelastic Scattering

Q: How would would you check if the nucleon is elementary ?

"High energy Rutherford experiment" firing an elementary probe to what you want to test as composite



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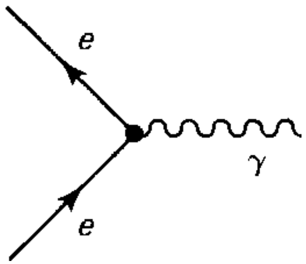
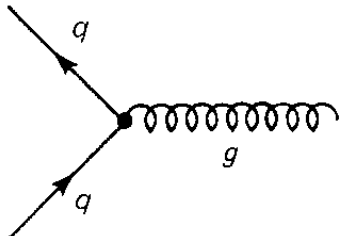
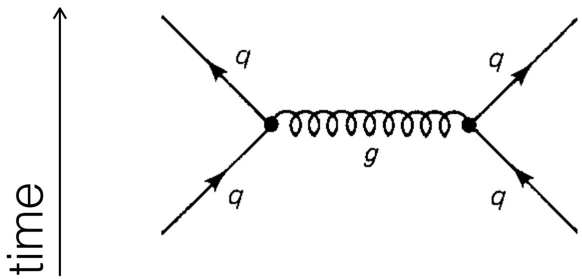
QFT - QCD

Quantum Chromo Dynamics (QCD) is a QFT which describes the strong interactions.

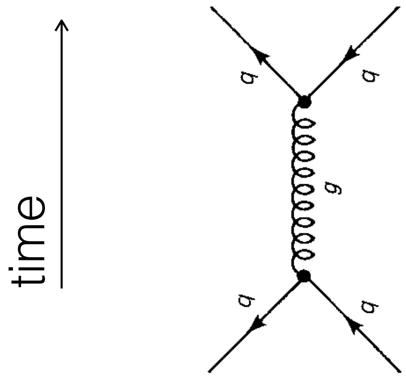
QED 

——> QCD 

As in QED physical processes are described using vertices as building blocks.



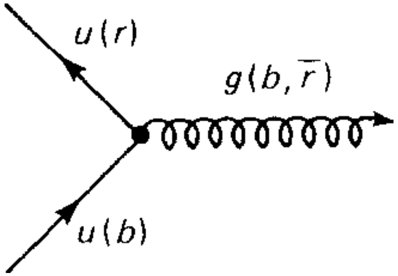
quark interaction
(quarks binding in the nucleon)



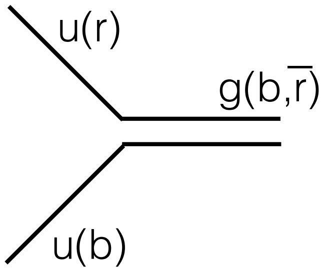
Particles going back in time are interpreted as anti-particles

QFT - QCD

Big difference: gluons have the same color-charge as quarks, photons are electrically-neutral!
(gluons are neutral wrt electric charge *photons are neutral wrt to color)*

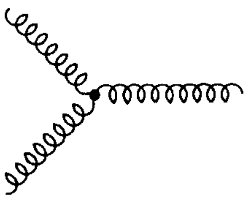


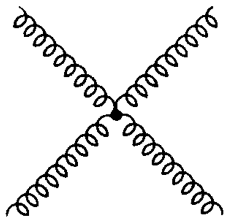
color is conserved at the vertex,
so the color-charged gluon has to have two colors !



A better notation to keep track of color

Carrying charge opens a wealth of new phenomena:





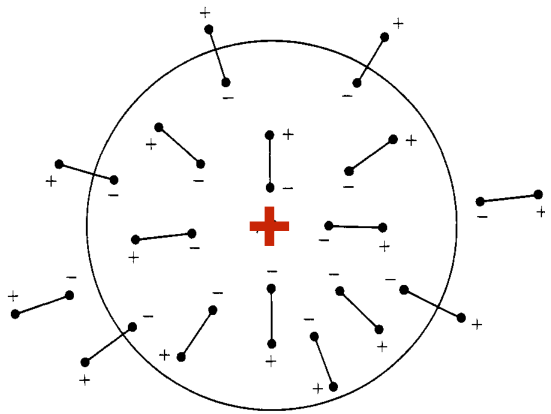
gluons interacts among themselves
(photons don't)

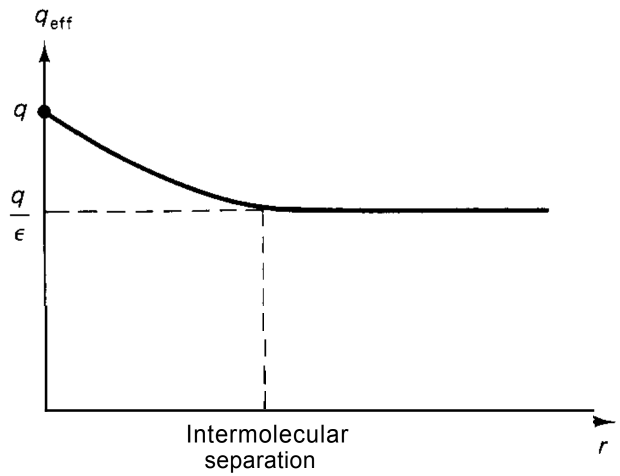
QFT - QCD

QED perturbation theory works because α is small (1/137) in QCD $\alpha_s > 1$

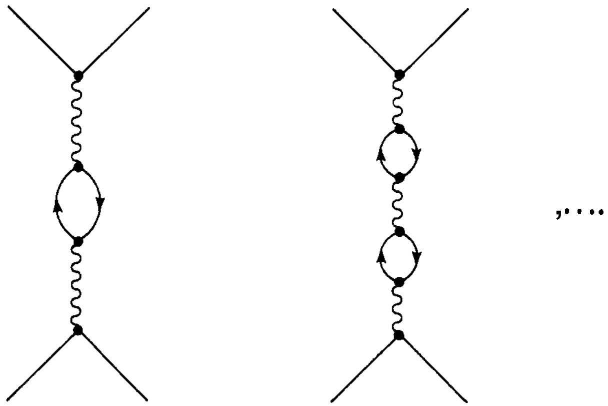
But fortunately *coupling constants are not constants !*

Running coupling constants: analogous to the dielectric polarization





A similar phenomenon happens in QED, where is the vacuum that gets polarized



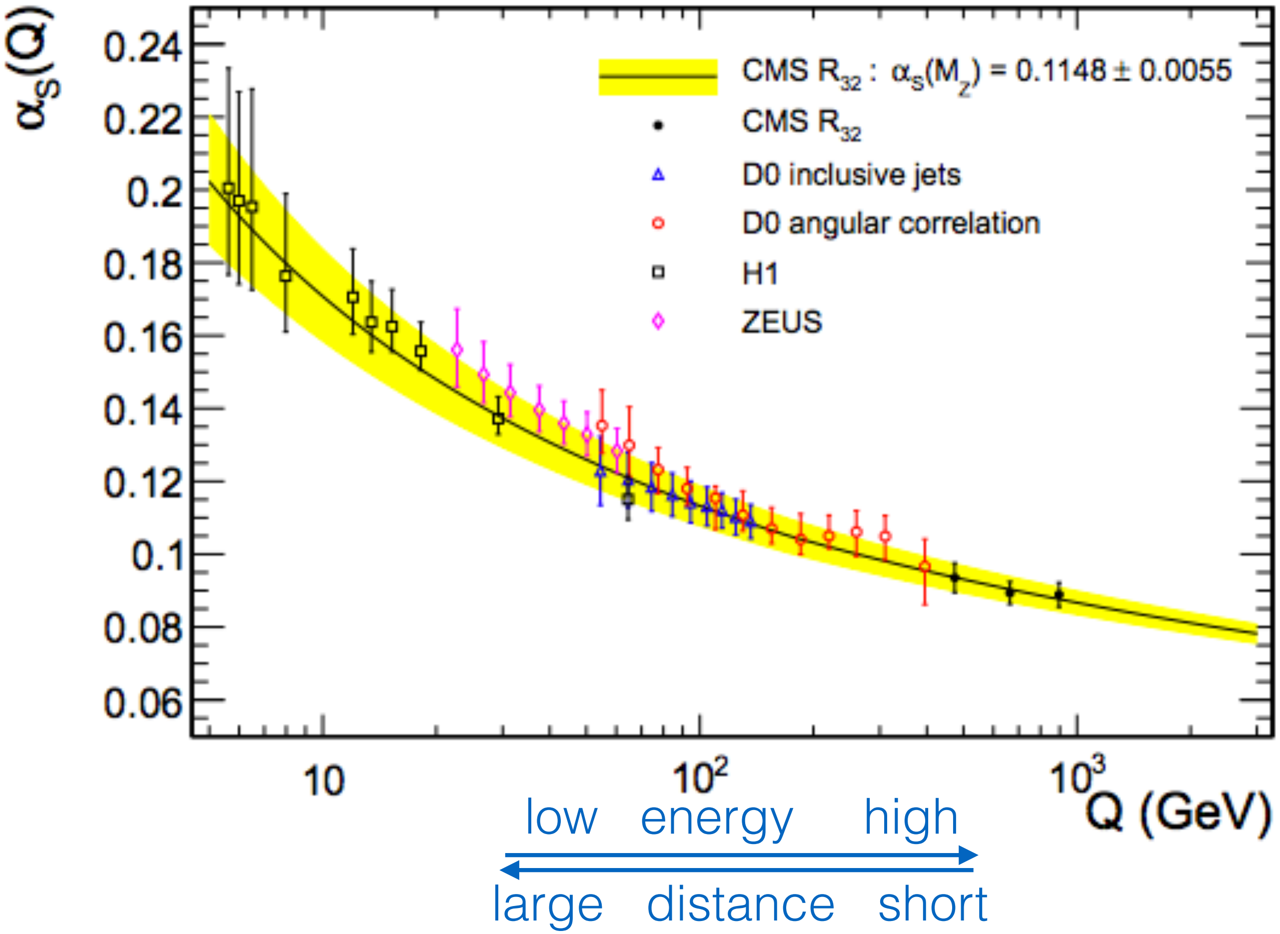
The virtual electrons gets attracted
the virtual positrons repelled.

So if you measure the electron charge at smaller and smaller distances (higher and higher energies you'll see it growing)

QFT - QCD

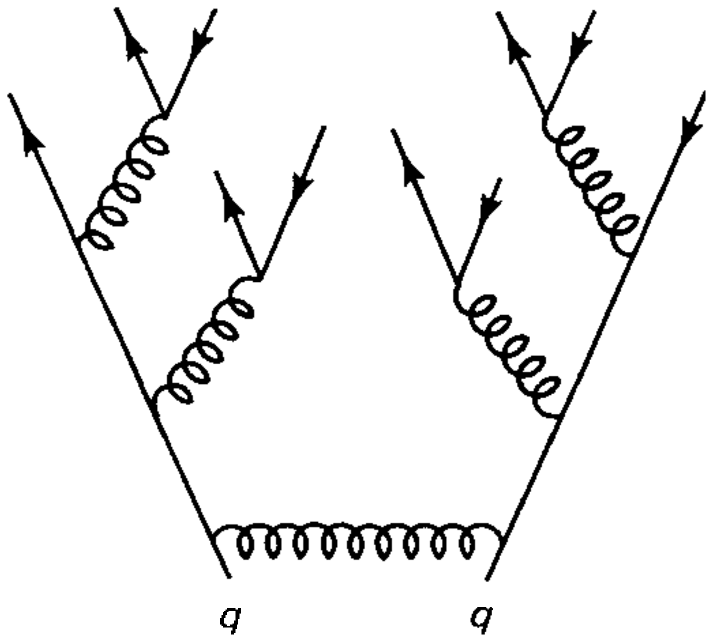
In QCD you have
- qqg vertex (as in QED) —> observed charge increase
- ggg / gggg vertices (not in QED) —> observed charge decrease

In QCD, the contributions the ggg / gggg wins an you observe a charge that decreases with smaller distances

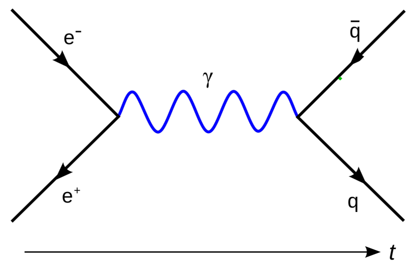


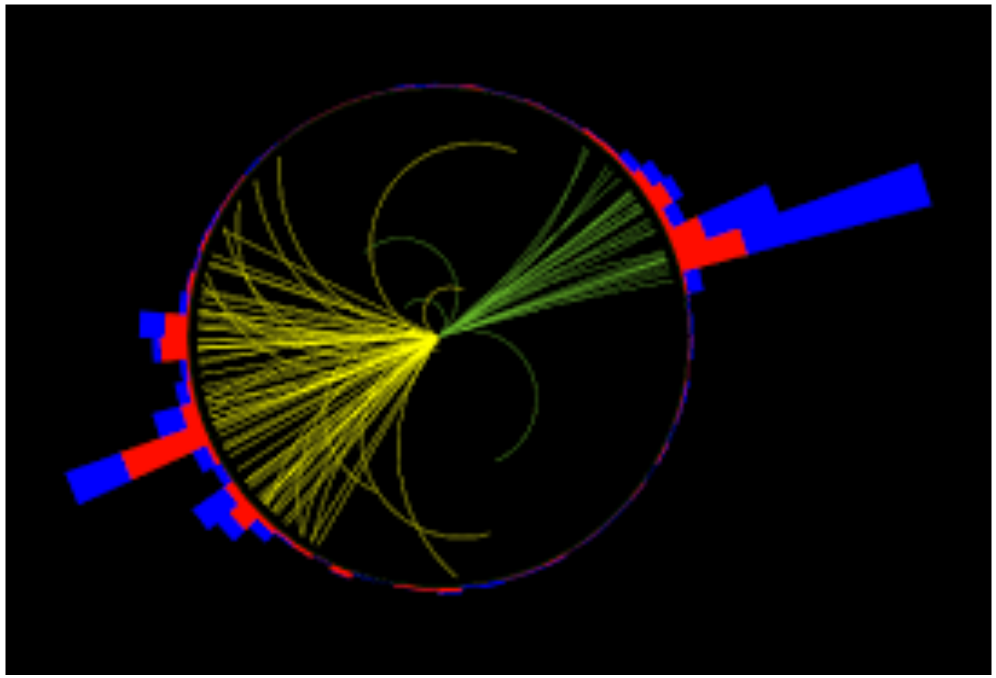
Jets

When produced, quarks will fly apart but they are not free !
the strong interaction between them is so great that new quarks-antiquarks pairs are created
Hadronization —> no coloured particle in the final state



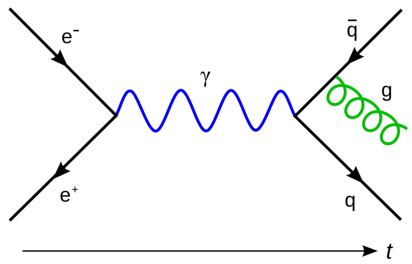
$e+e- \longrightarrow q\,\bar{q}$

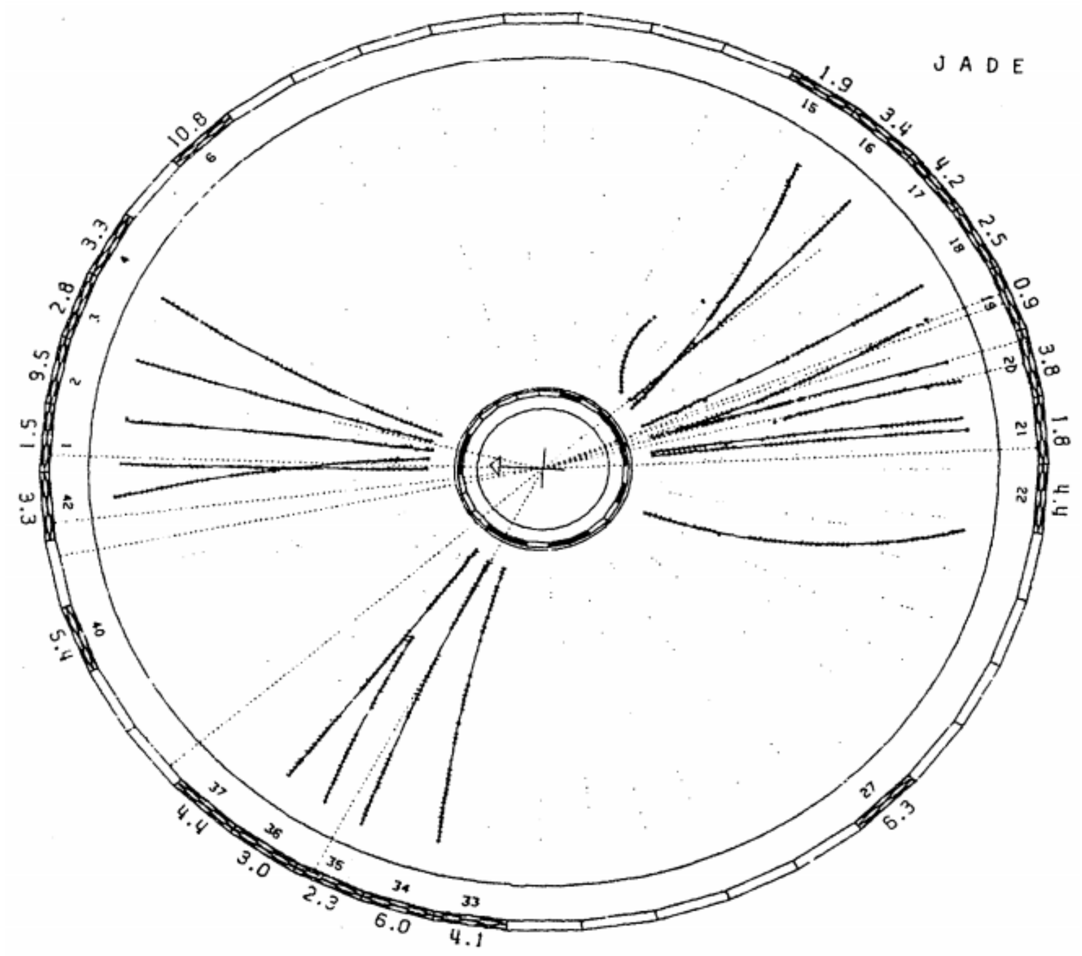




Gluon

e+e- —> q q̄ g





Jade @ PETRA
Positron Electron Tandem Ring Accelerator - Desy

Generations

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(—> Feynman partons)
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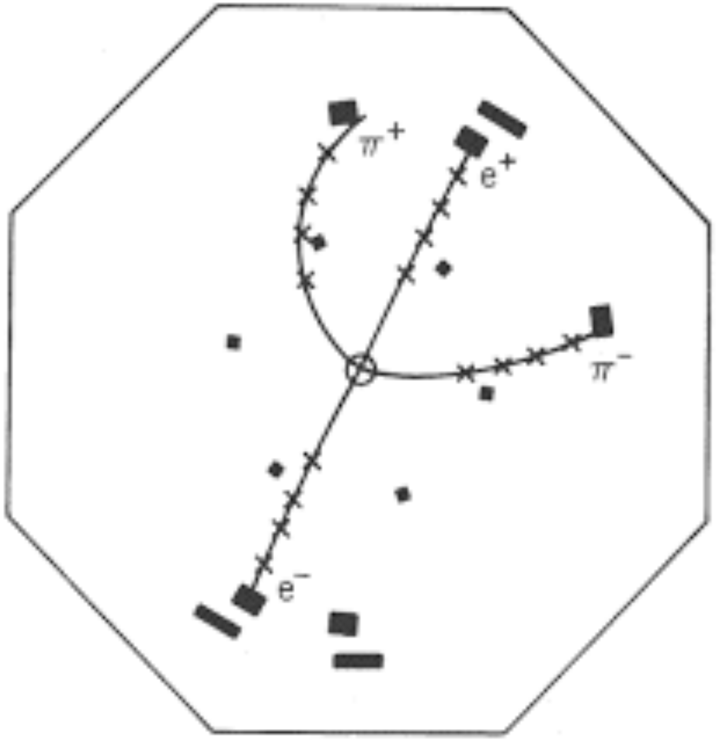
1974 November revolution J/psi discovery Richter/Ting BNL/SLAC
charm quark (but J/psi no "net" charm, it's a c-\bar{c} bound state)

u c q= 2/3
d s q= -1/3

J/psi



psi’—>psi pi+ pi-

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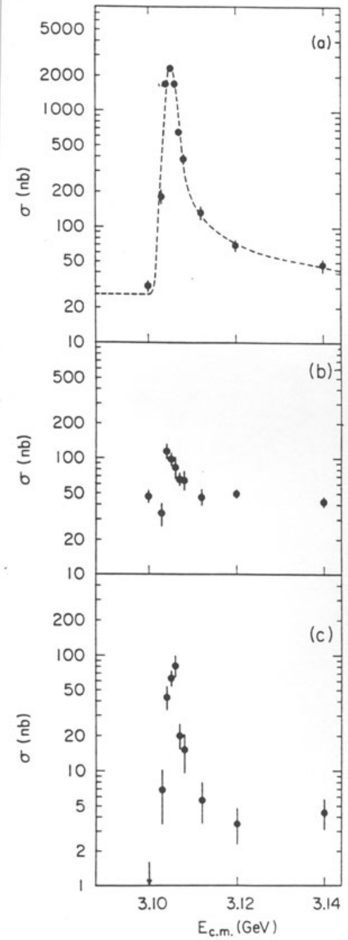

ꟻIG. 1. Cross section versus energy for (a) multi-
iron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$,
π^-, and K^+K^- final states. The curve in (a) is the ex-
cted shape of a δ-function resonance folded with the
ussian energy spread of the beams and including
diative processes. The cross sections shown in (b)

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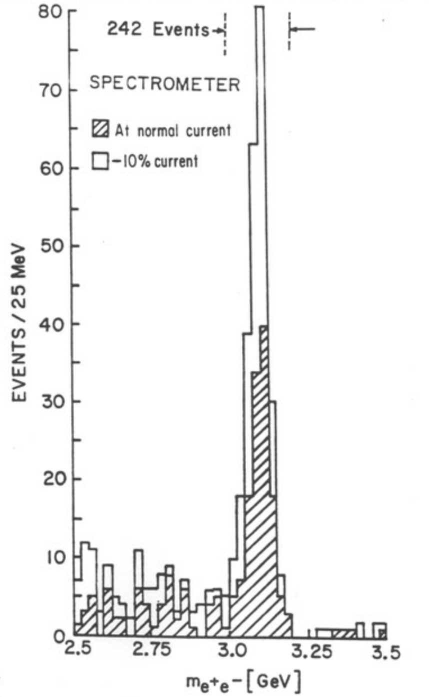
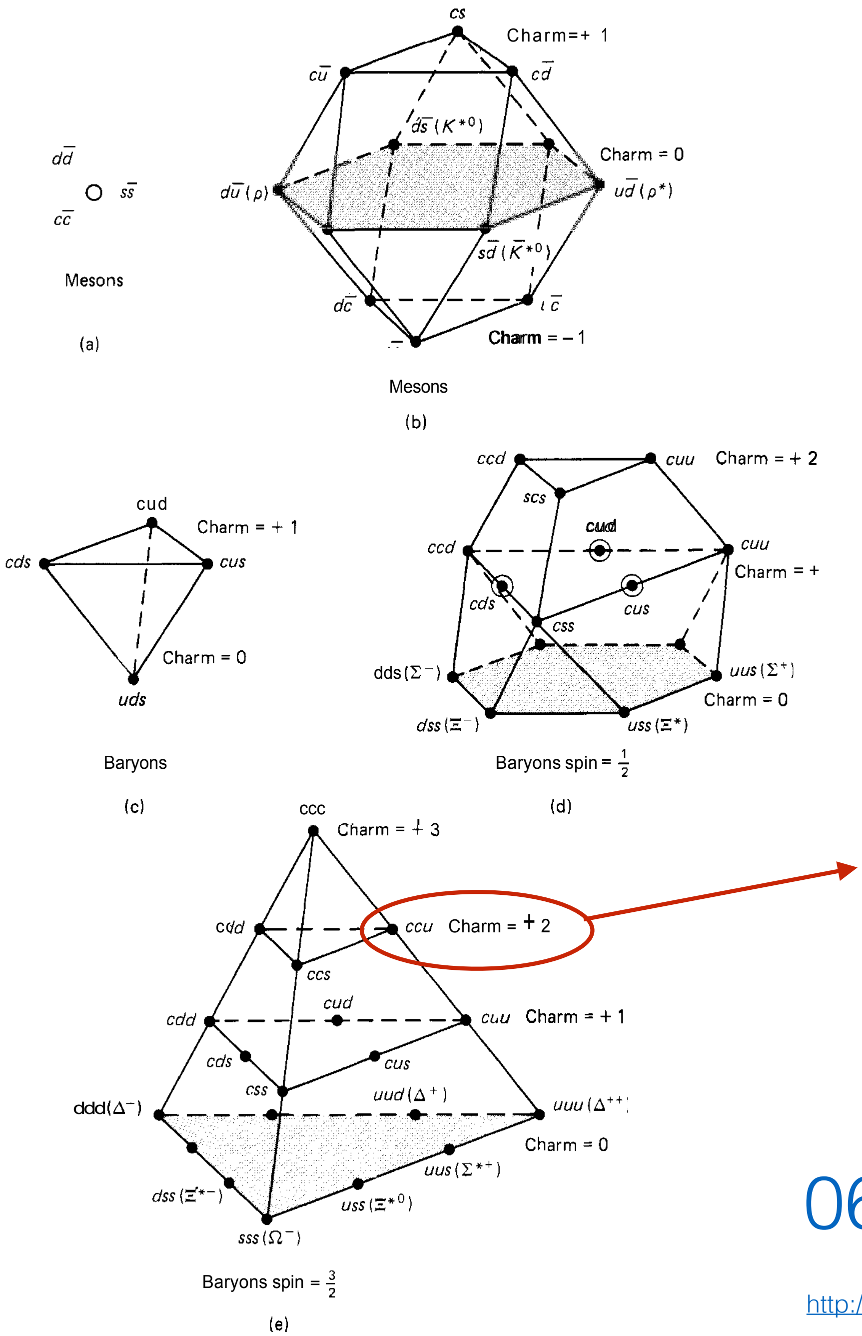


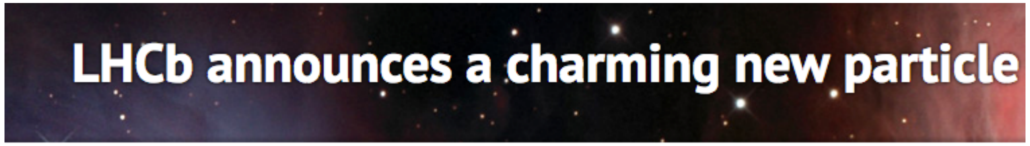
ꟻIG. 2. Mass spectrum showing the existence of J.
sults from two spectrometer settings are plotted
owing that the peak is independent of spectrometer
rents. The run at reduced current was taken two
nths later than the normal run.

The explanation that won about the origin of the J/psi is the one of the quark model !

The J/psi is very long lived 10^{-20} seconds (typically hadrons decay in 10^{-23} seconds)
The decay proceeds through the weak interaction.

Multiplets with four quarks (udcs)





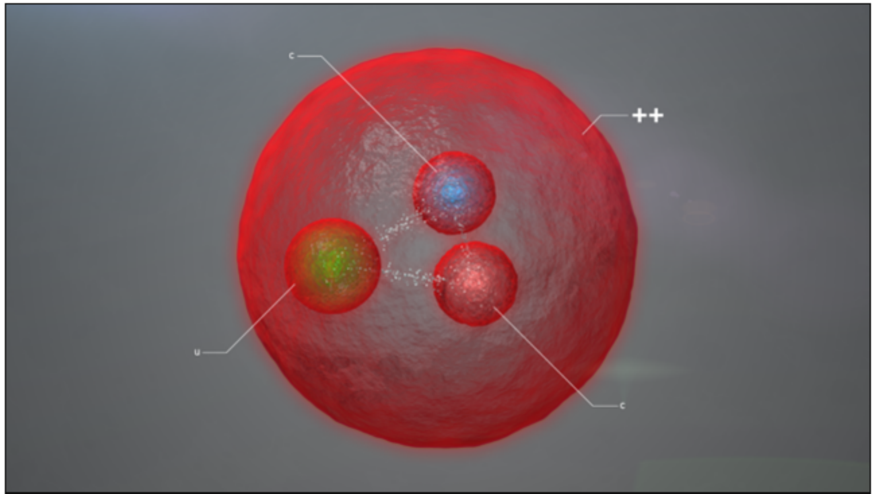
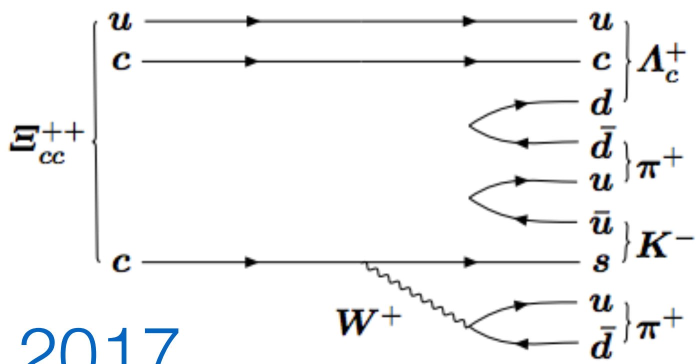


Image representing the new particle observed by LHCb, containing two charm quarks and one up quark. (Image: Daniel Dominguez/CERN)



06.07.2017

http://press.web.cern.ch/sites/press.web.cern.ch/files/file/press/2017/07/lhcb_paper_2017.07.06.pdf

Generations

Δ^{++} against Pauli principle: it's a bound state of 3 up-quarks all in the same state (symmetric)
1964 Greenberg proposes a new quantum number: color
The three up quarks do not violate Pauli principle because they come in different colors RGB (antisymmetric)
New principle: All hadrons are color-less and the only combinations that one can make are:
baryons: 3 quarks (RGB) - antibaryons 3 antiquarks (RBG)
mesons: quark-antiquark (RRbar, GGbar, BBbar)

No free quark ever observed.
1969 DIS Friedmann, Kendall, Taylor
(—> Feynman partons)
1973 Confinement / Asymptotic freedom (Gross, Politzer, Wilczek)

1974 November revolution J/psi discovery Richter/Ting BNL/SLAC
charm quark (but J/psi no "net" charm, it's a c-\bar{c} bound state)

1975 naked charm Lambda_c+ (udc)
1976 D0 (c anti-u) D+ (c anti-d)
1977 Ds (c anti-s)

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1975 tau - first LEPTON of the third leptonic generation

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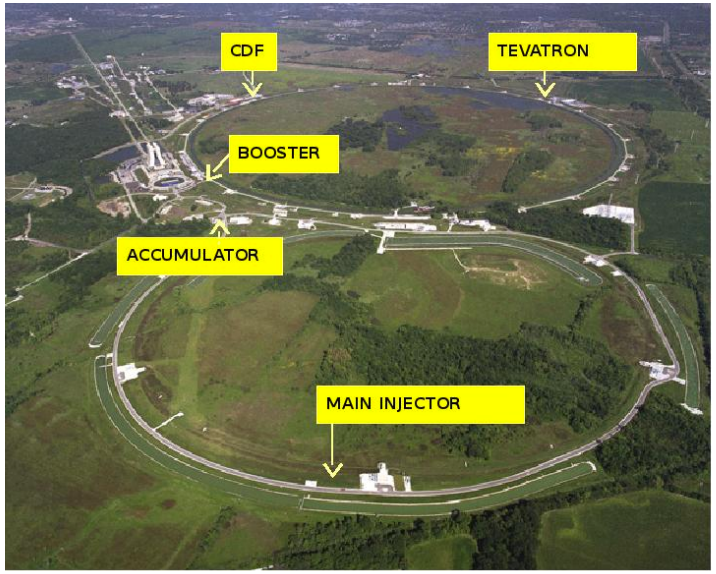
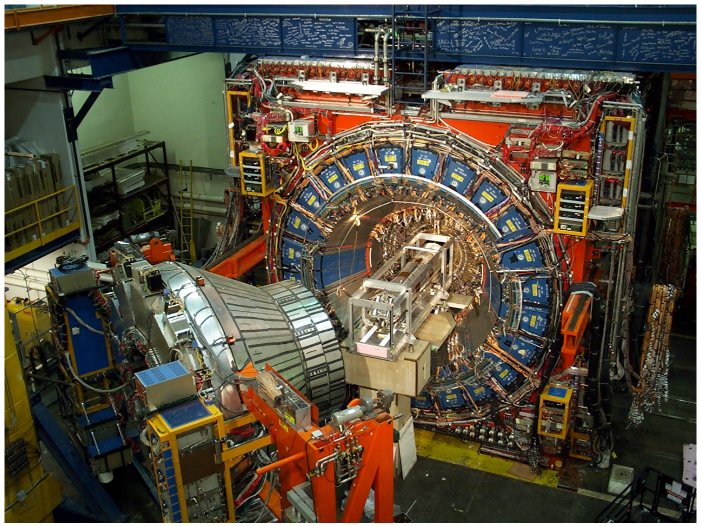
1976 D0 (c anti-u) D+ (c anti-d)
1977 Ds (c anti-s)
1975 tau - first LEPTON of the third leptonic generation
1977 Ypsilon b-bbar: first particle of the quark third gerenation
1981 Lambda_b (udb)
1983 Bd (b-antid)
1994 top-quark discovery at TeVatron

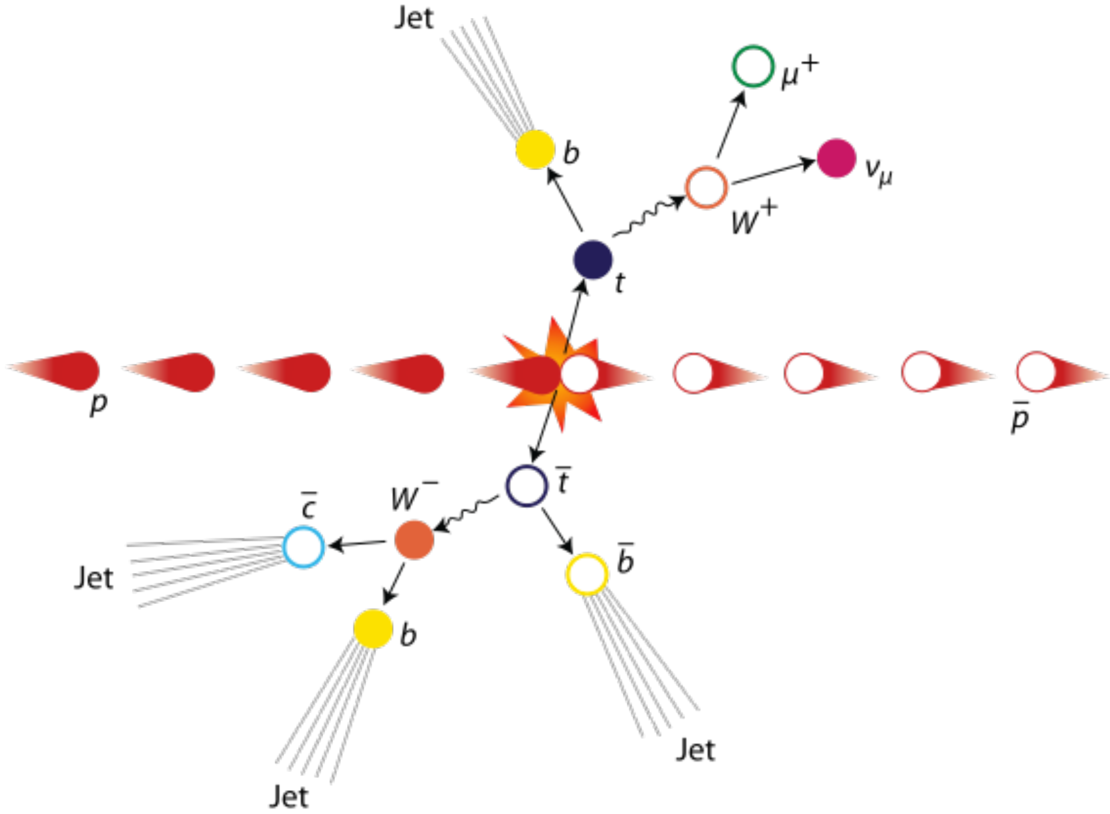
u c t q= 2/3
d s b q= -1/3

Top discovery

Discovered at Fermilab



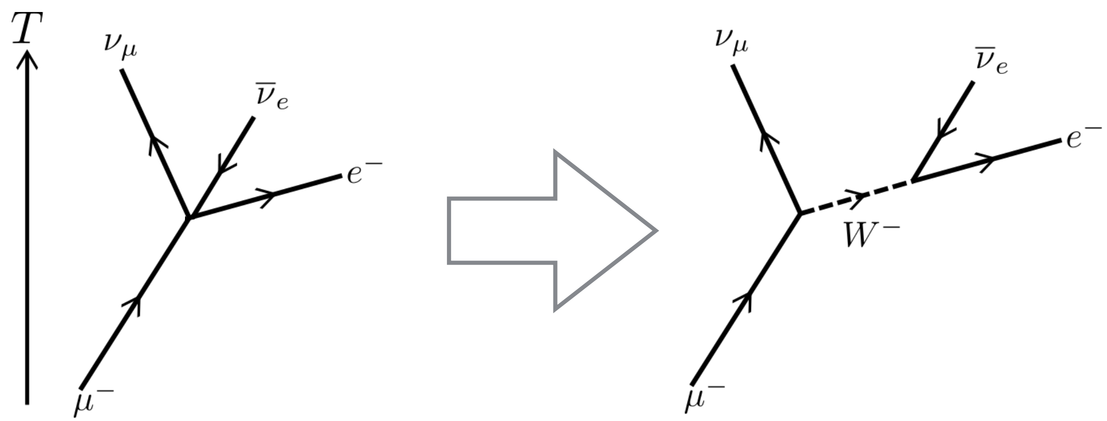




Top decays before “hadronizing”

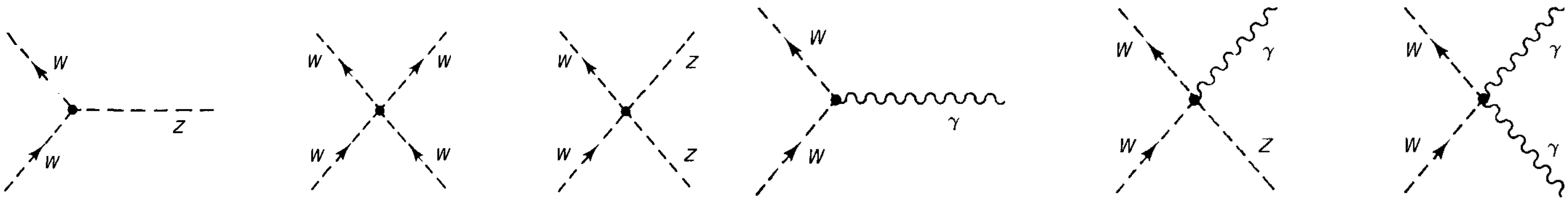
GWS + Higgs

Fermi Theory of beta decay:contact interaction
Weak force has a very short range (i.e. easy to approximate by a contact interaction).
But at high energy (when you start probing short distances) Fermi theory fails



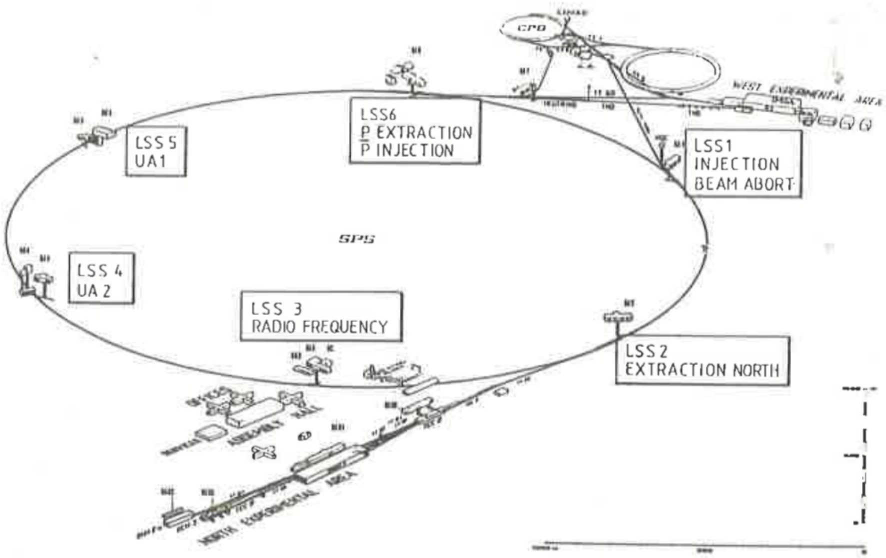
Steven Weinberg https://home.cern/news/obituary/cern/steven-weinberg-1933-2021

Glashow (1961) - Higgs (1964) - Weinberg (1967) - Salam (1968)
Electromagnetism and Weak interactions are unified —> EW part of the SM
Photon-Z-W mass pattern from Higgs mechanism (spontaneous EW symmetry breaking)

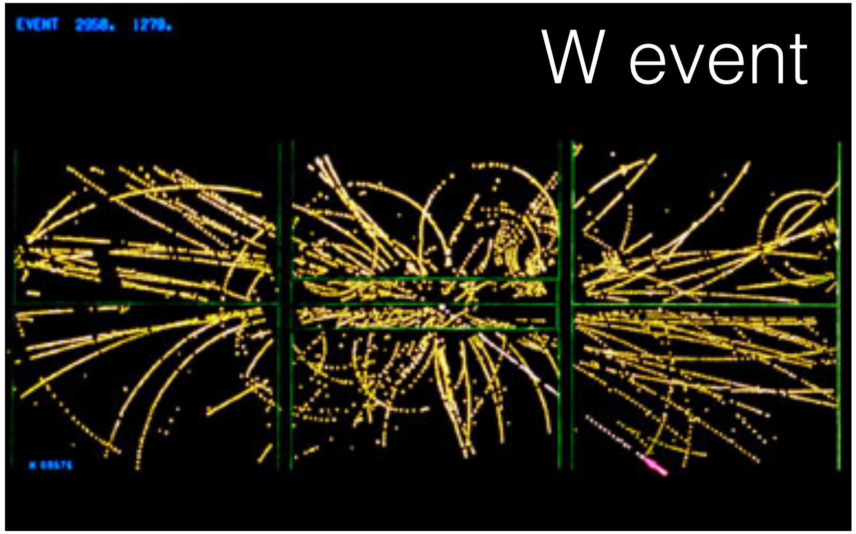


1983 Rubbia, Van der Meer: discovery W/Z at the predicted mass

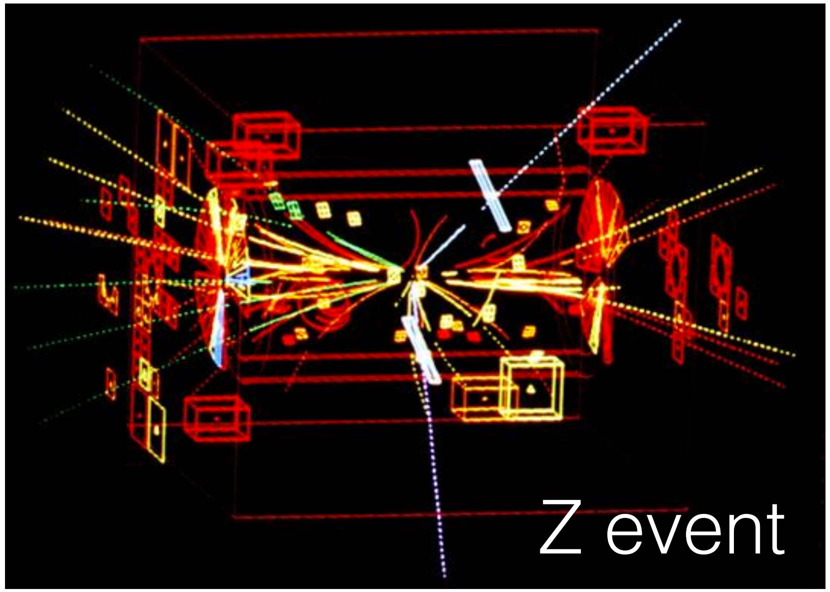
UA1 UA2



LSS6
P EXTRACTION
P INJECTION
LSS 5
UA1
LSS1
INJECTION
BEAM ABORT
SPS
LSS 4
UA 2
LSS 3
RADIO FREQUENCY
LSS 2
EXTRACTION NORTH



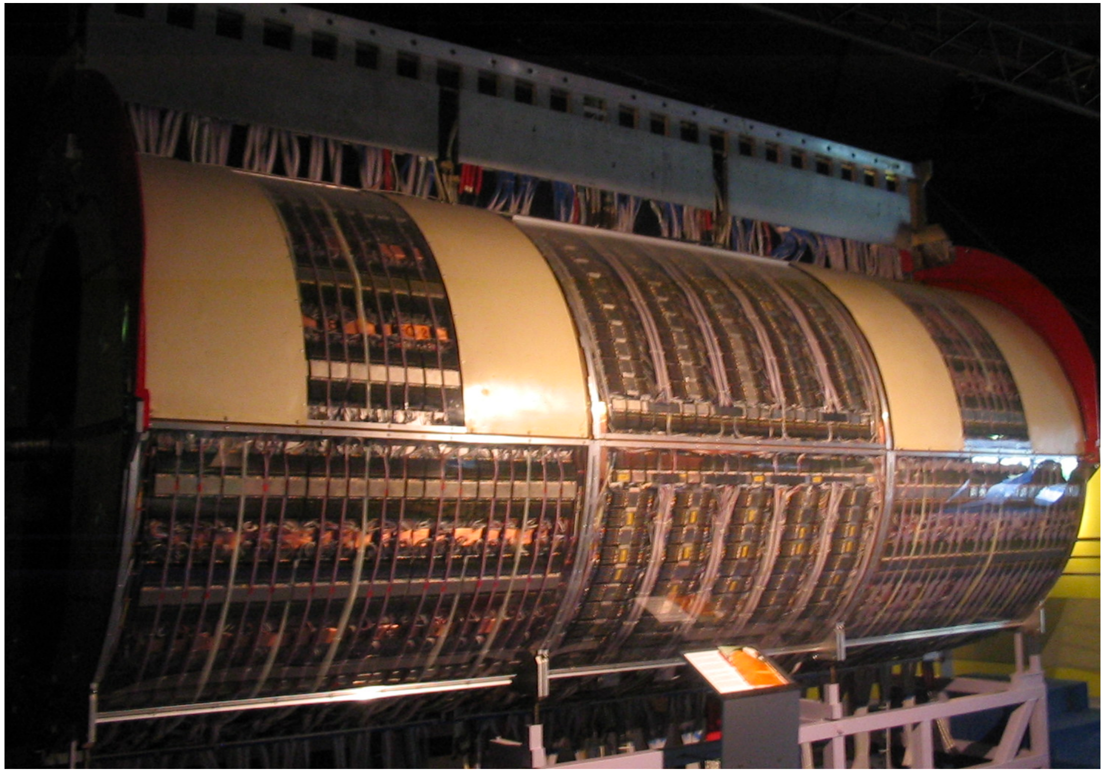
W event

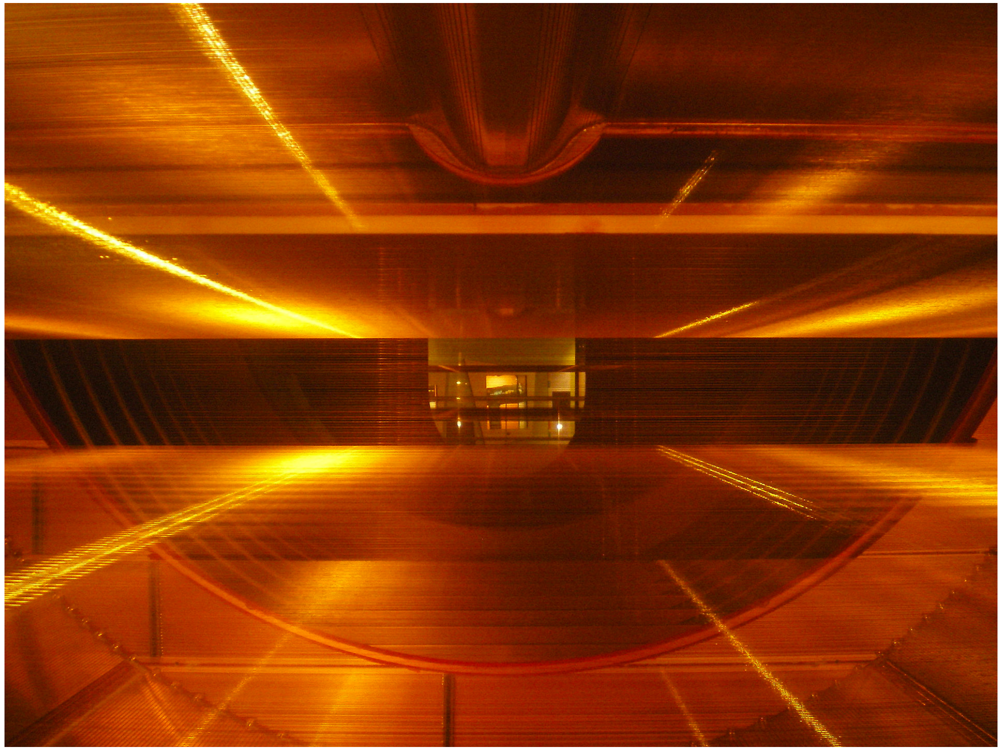


Z event

UA1

Drift chamber

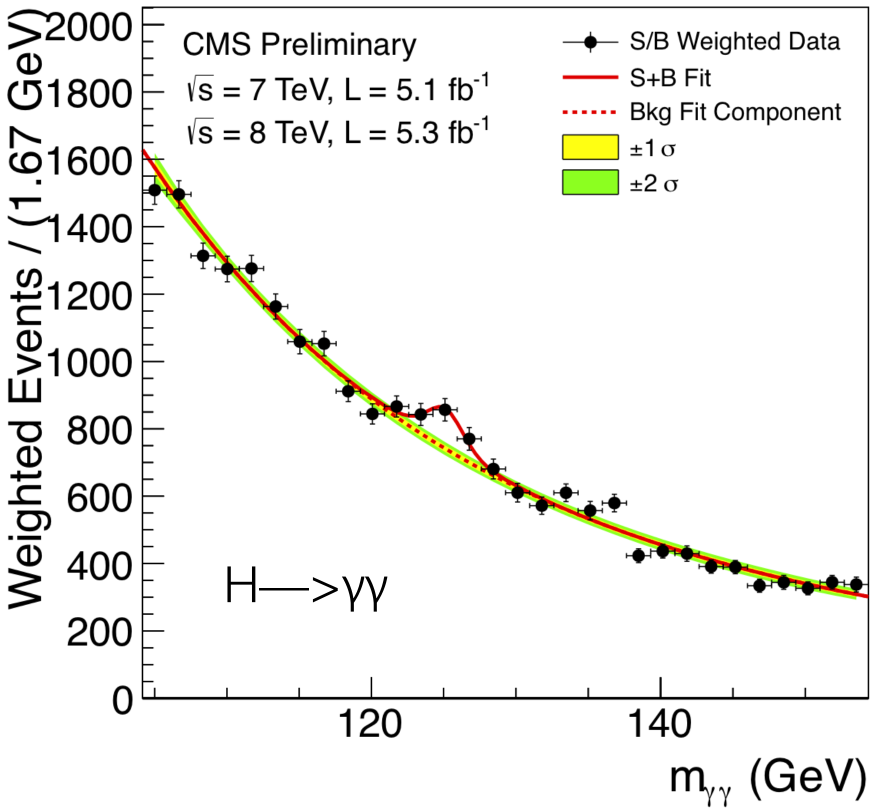


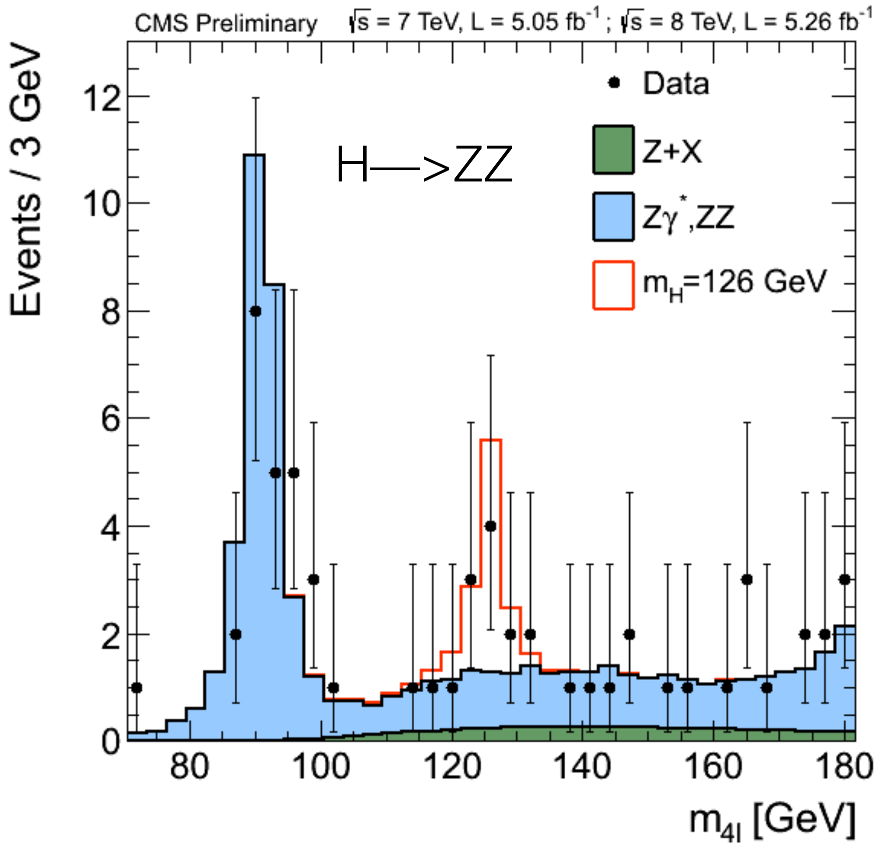


Higgs boson

The Higgs field is responsible for the spontaneous EW symmetry breaking
(the underlying lagrangian has a symmetry but the solutions do not)
which allows W+- and Z bosons to acquire a mass and the photon to remain massless

Everything was fitting perfectly the GSW model, but for ~40 years there was no sign of the Higgs boson.
2012 Discovery of the Higgs boson by ATLAS and CMS

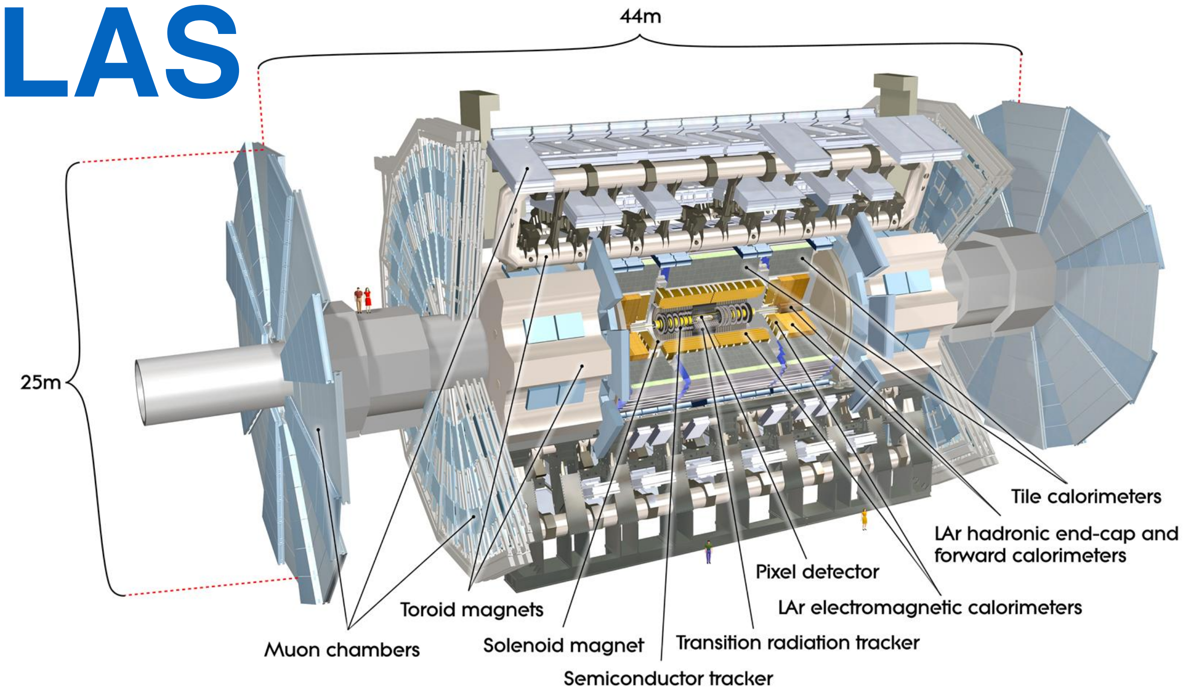


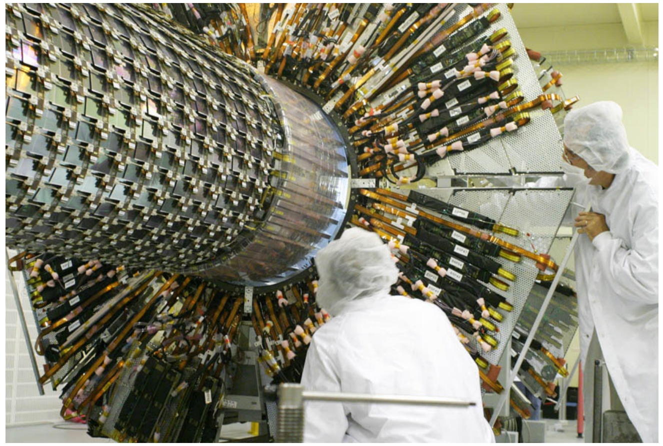


LHC

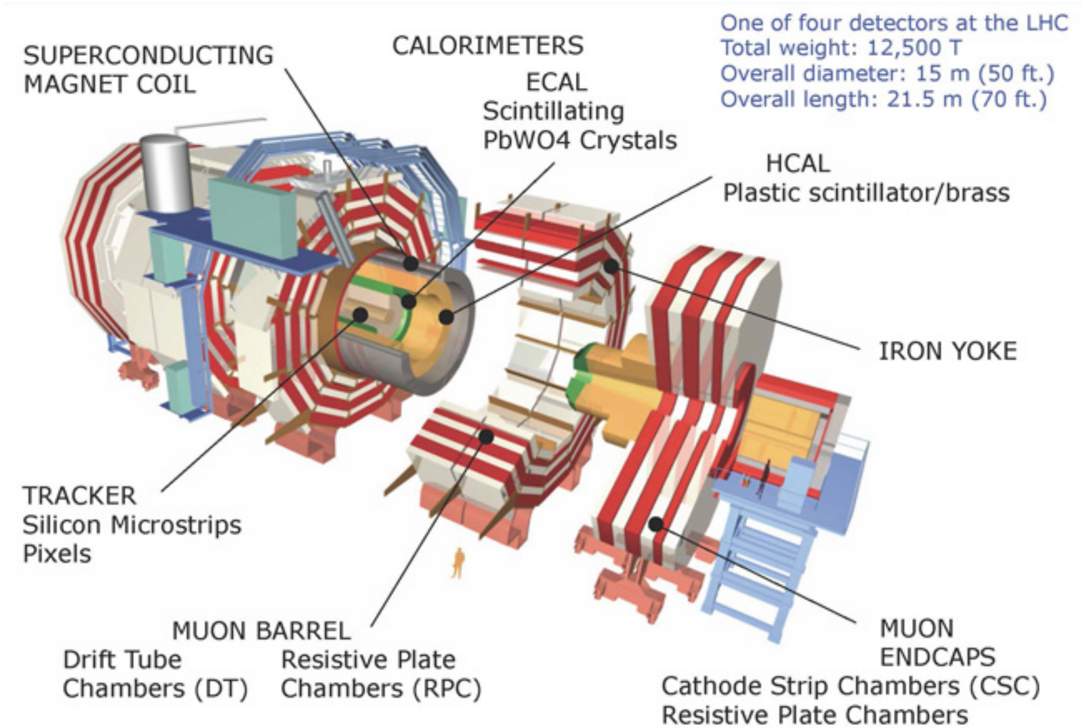
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
LHC 27 km

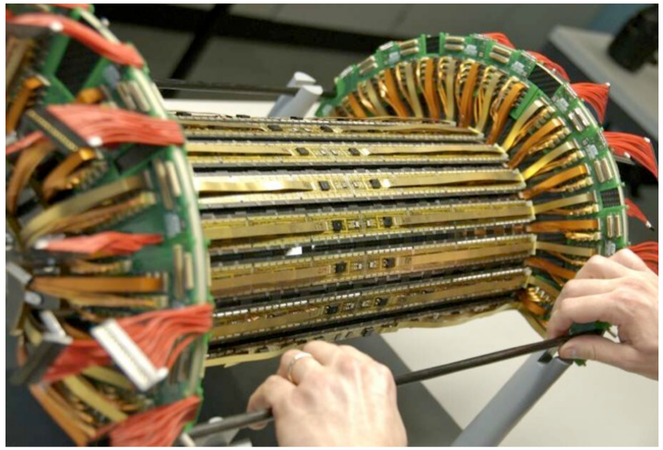
ATLAS


44m
25m
Tile calorimeters
LAr hadronic end-cap and forward calorimeters
Pixel detector
LAr electromagnetic calorimeters
Toroid magnets
Muon chambers
Solenoid magnet
Transition radiation tracker
Semiconductor tracker



CMS


SUPERCONDUCTING MAGNET COIL
CALORIMETERS
ECAL
Scintillating PbWO4 Crystals
One of four detectors at the LHC
Total weight: 12,500 T
Overall diameter: 15 m (50 ft.)
Overall length: 21.5 m (70 ft.)
HCAL
Plastic scintillator/brass
IRON YOKE
TRACKER
Silicon Microstrips
Pixels
MUON BARREL
Drift Tube Chambers (DT)
Resistive Plate Chambers (RPC)
MUON ENDCAPS
Cathode Strip Chambers (CSC)
Resistive Plate Chambers



Weak interaction

Both leptons and quarks experience weak interactions

Q: what forces/interactions feel leptons, neutrino, quarks ?

Weak interaction

Q: what are the charges of the leptons, neutrino, quarks ?

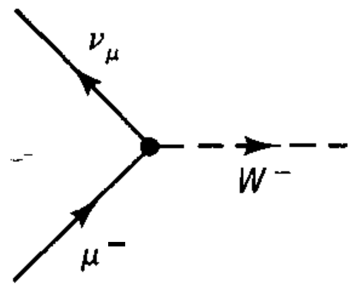
Charged leptons (e, mu, tau): electric, weak
Neutrinos: weak only
quarks: electric, color, weak

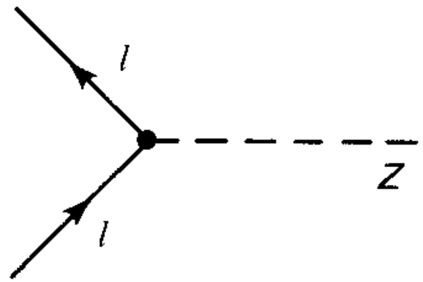
(…and gravitational force)

Weak interaction

Both leptons and quarks experience weak interactions

The basic vertices of the weak interactions are:





Q: Can you draw the muon decay and the nu-e elastic scattering ?

Weak interaction

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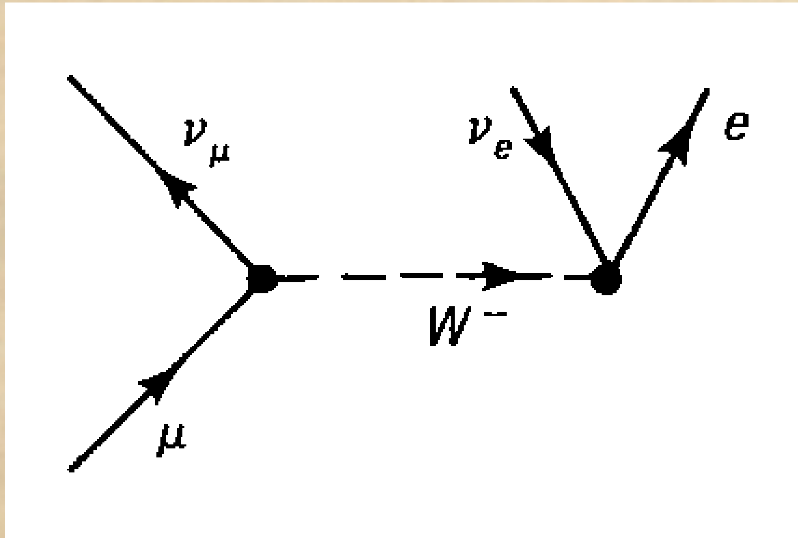

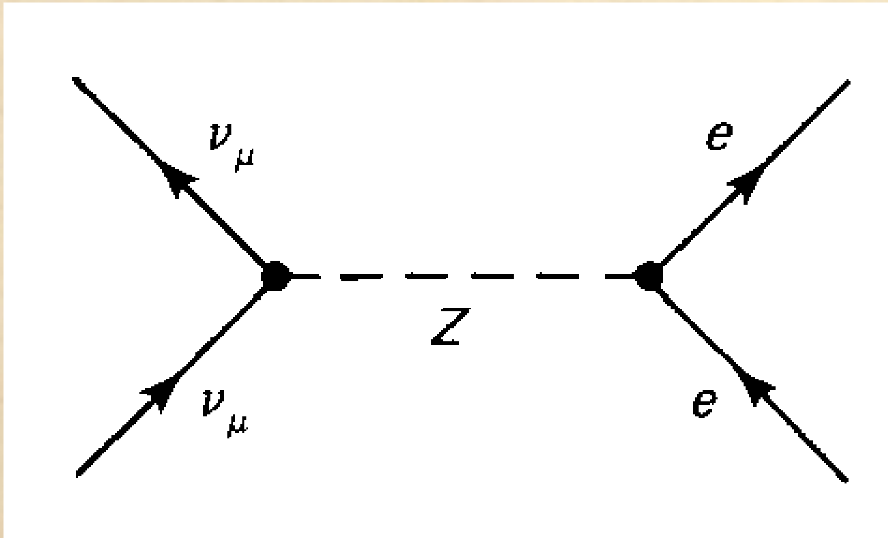

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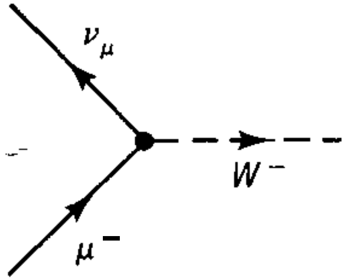
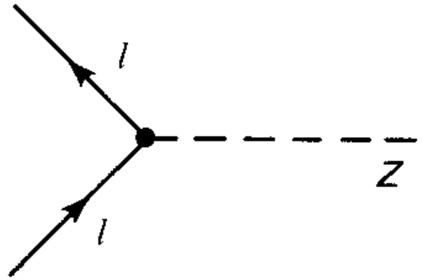
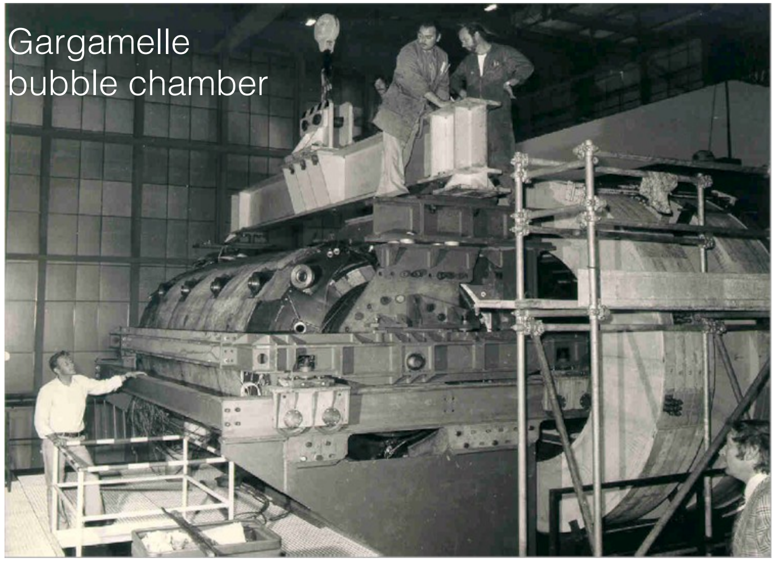


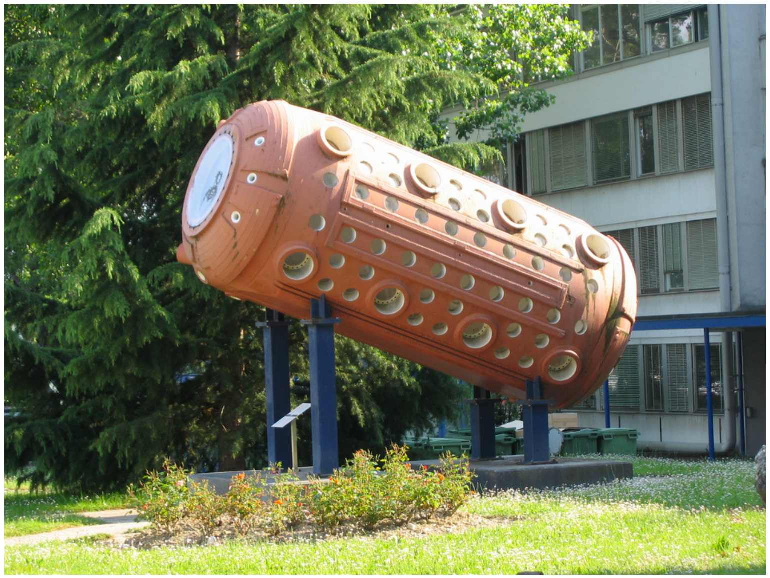


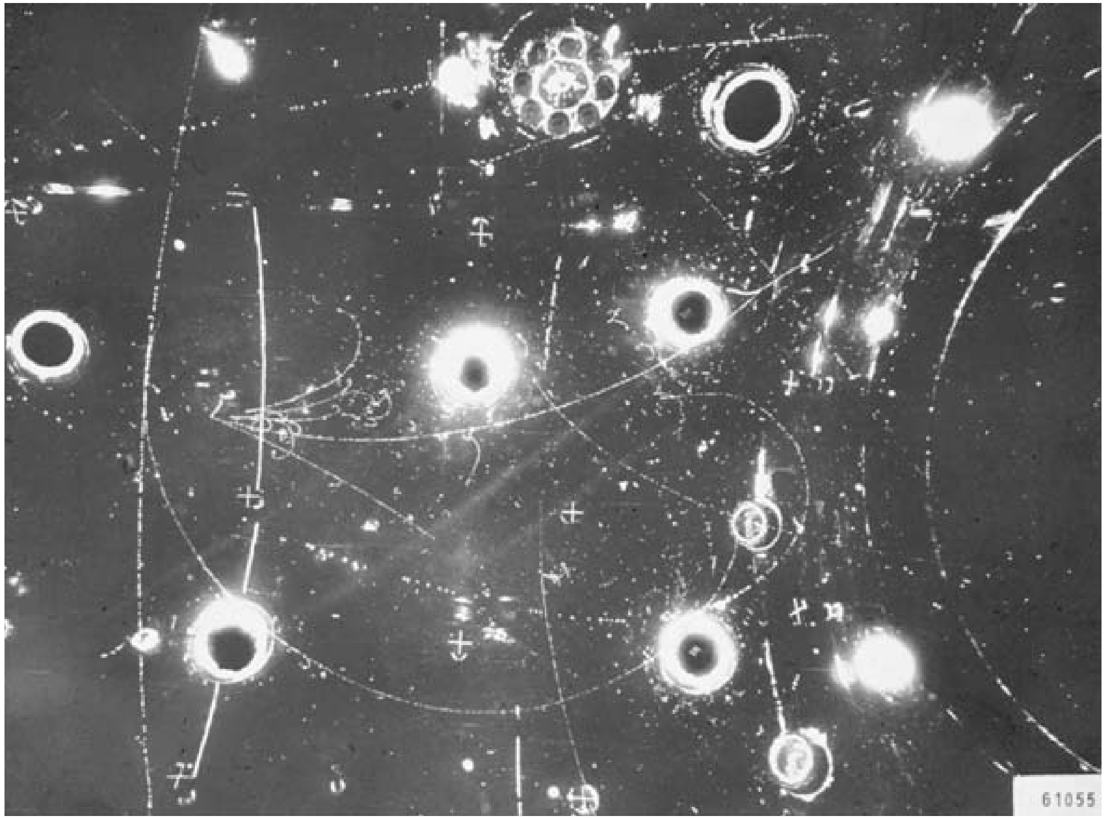
W-vertex “idea was there from the beginning” (beta decay)
1968 Z-vertex in GWS model
1973 Gargamelle: neutral currents at CERN
main difficulty large backgrounds from electromagnetic effects (photons and neutron backgrounds) DESY (Tasso) showed the Z-contribution through asymmetries, but only nu-scattering, where em =interaction is off offers a clear signature)

Weak interaction

Neutral currents: A perfect experimental discovery
http://cerncourier.com/cws/article/cern/54388





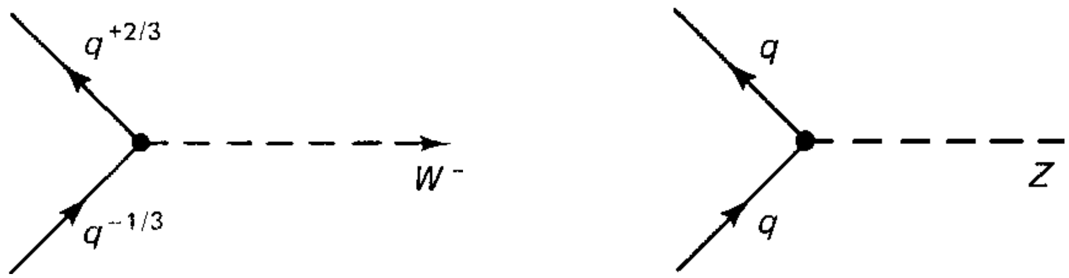


$$\nu_\mu + N \rightarrow \nu_\mu + \text{hadrons}$$

No muons in the final state ! (see Bettini Sec 7.10)

Weak interaction

Quarks: the basic vertices are



Q: Can you draw the diagram of the weak decay of the neutron ?
and the pion decay ?
and the neutrino proton elastic scattering?

Weak interaction

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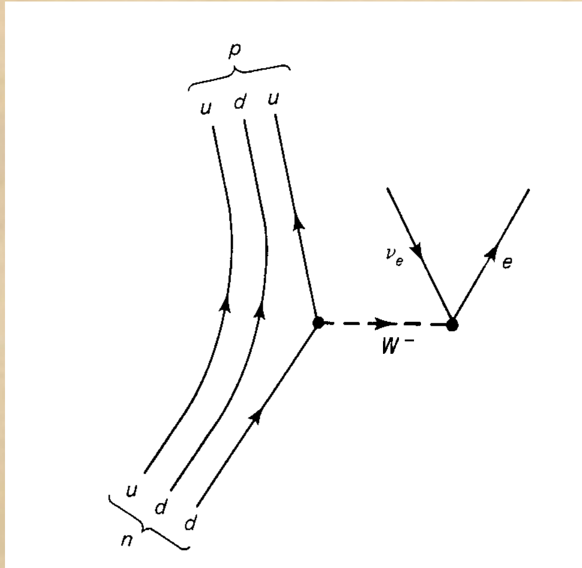

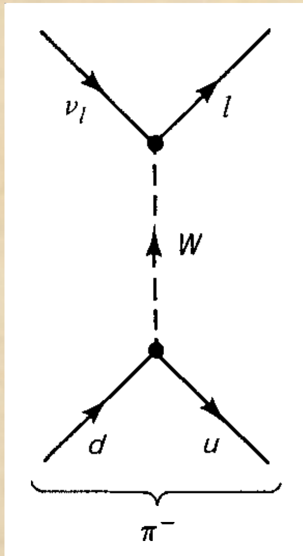

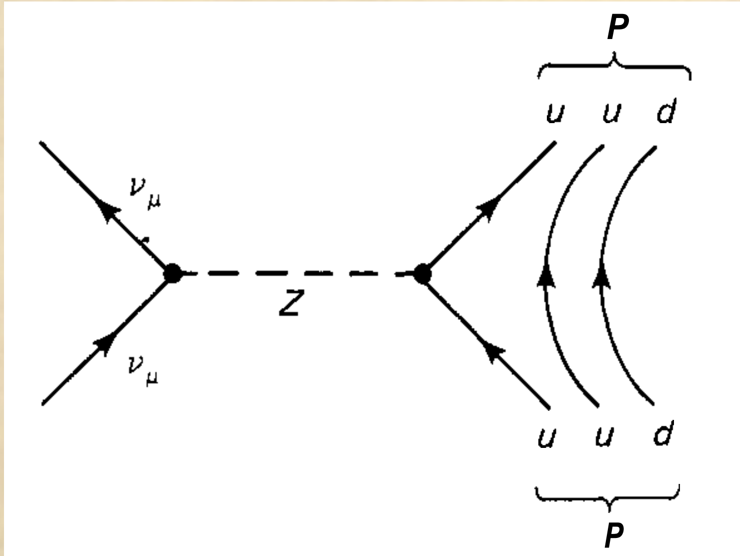

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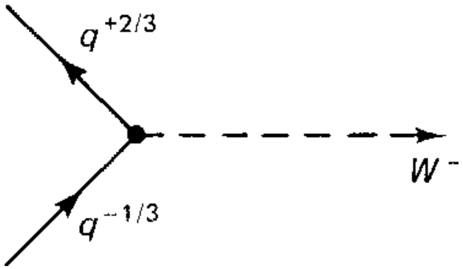
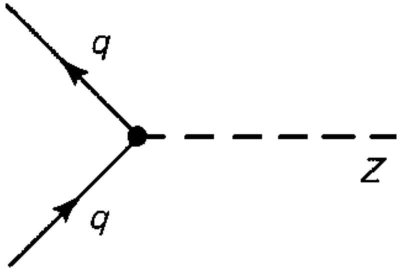
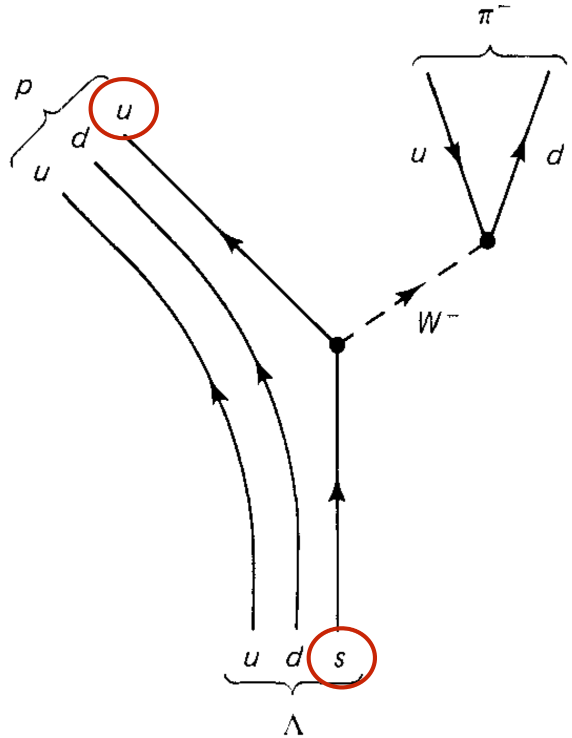




But there is much more !
The weak interactions does not respect quarks generations
1963 Cabibbo angle
1970 GIM mechanism
1973 CKM matrix



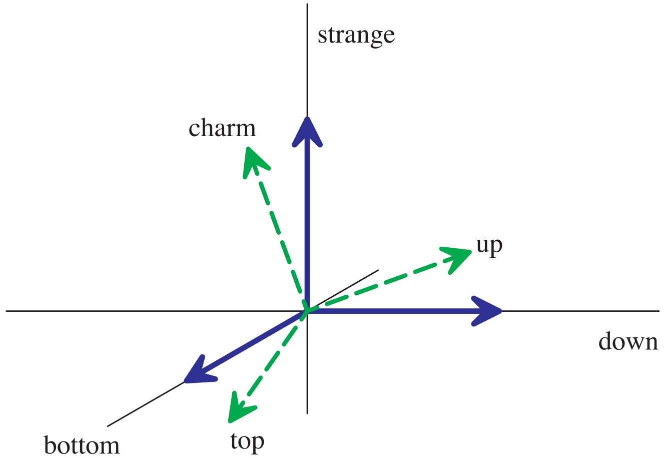
$$\begin{pmatrix} u \\ d \end{pmatrix}, \quad \begin{pmatrix} c \\ s \end{pmatrix}, \quad \begin{pmatrix} t \\ b \end{pmatrix} \quad \Rightarrow \quad \begin{pmatrix} u \\ d' \end{pmatrix}, \quad \begin{pmatrix} c \\ s' \end{pmatrix}, \quad \begin{pmatrix} t \\ b' \end{pmatrix}$$

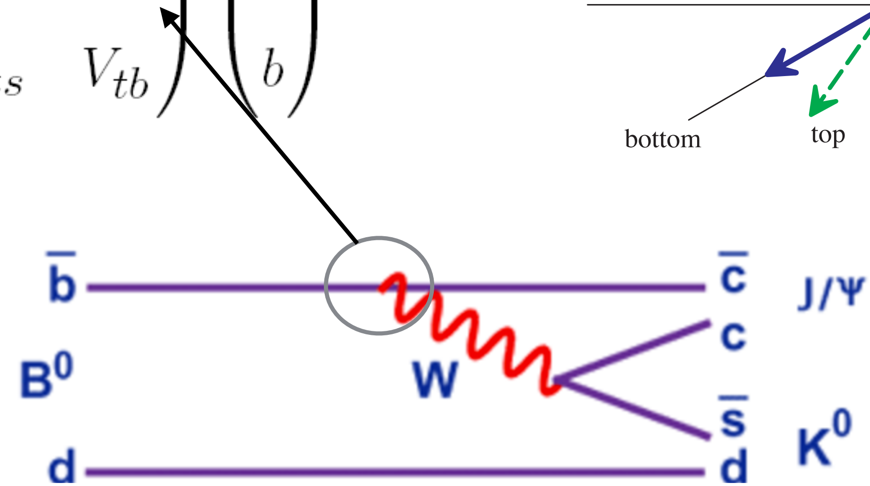
quark flavours “are mixed”

Weak interaction

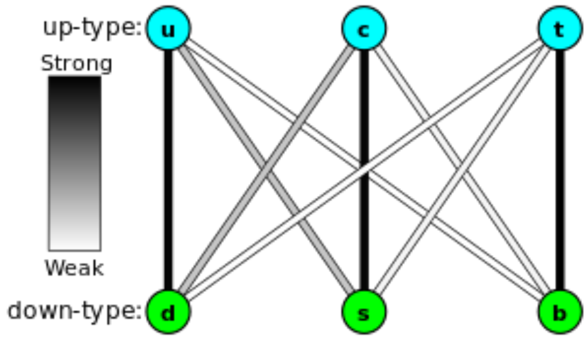
CKM matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$





$$V_{\rm CKM} = \begin{pmatrix} 0.97427 \pm 0.00014 & 0.22536 \pm 0.00061 & 0.00355 \pm 0.00015 \\ 0.22522 \pm 0.00061 & 0.97343 \pm 0.00015 & 0.0414 \pm 0.0012 \\ 0.00886^{+0.00033}_{-0.00032} & 0.0405^{+0.0011}_{-0.0012} & 0.99914 \pm 0.00005 \end{pmatrix}$$

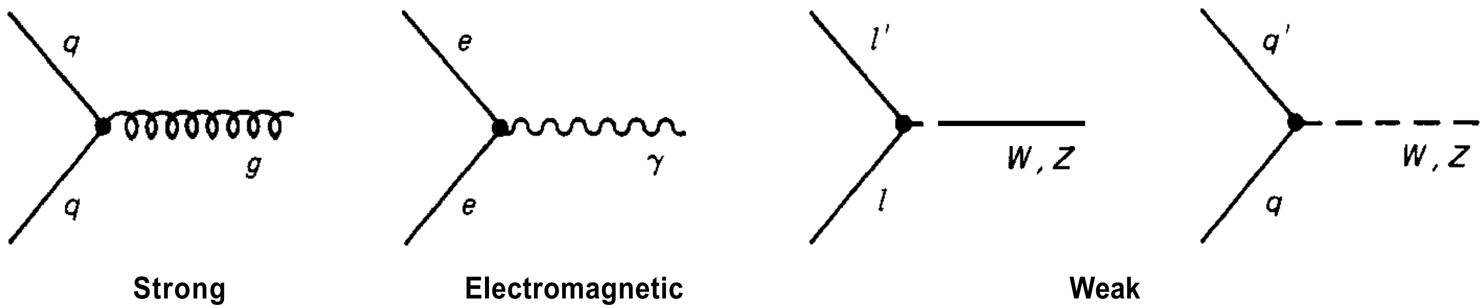


Conservation laws

"Whatever is not explicitly forbidden is mandatory"

Kinematic conservation laws:
  Energy-Momentum
  Angular momentum
These apply to all interactions !
They come from space-time (translation space-time, rotation) symmetries

To obtain the conservation laws of a theory, take the fundamental vertices: everything that is conserved at the vertex level, must be conserved in any complex process



Q: what conservation laws can you extract from these vertices ?

Conservation laws

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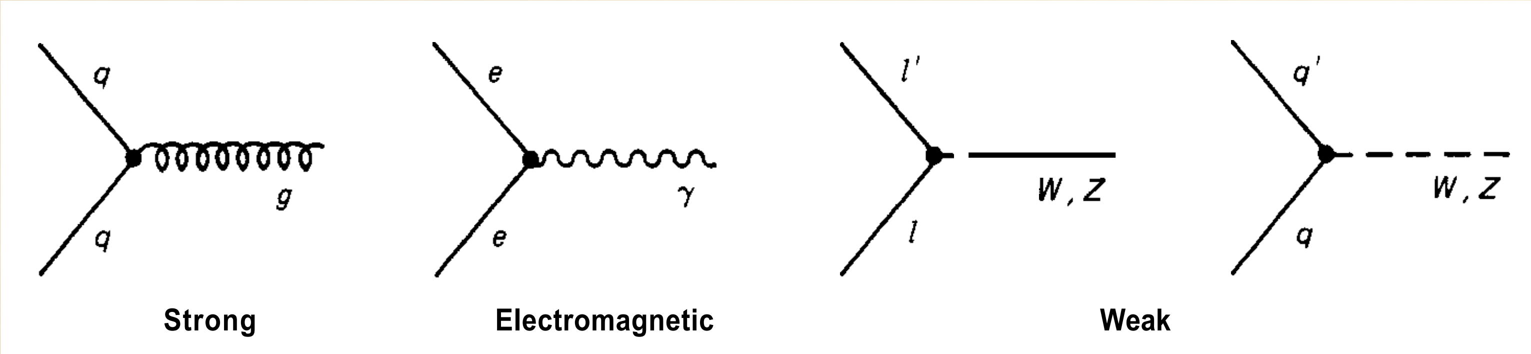

Electric charge
Color
Baryon number (quarks count +1/3, anti-quarks count -1/3)
Lepton number (but neutrino mixing)

Conservation laws

"Whatever is not explicitly forbidden is mandatory"

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  Angular momentum
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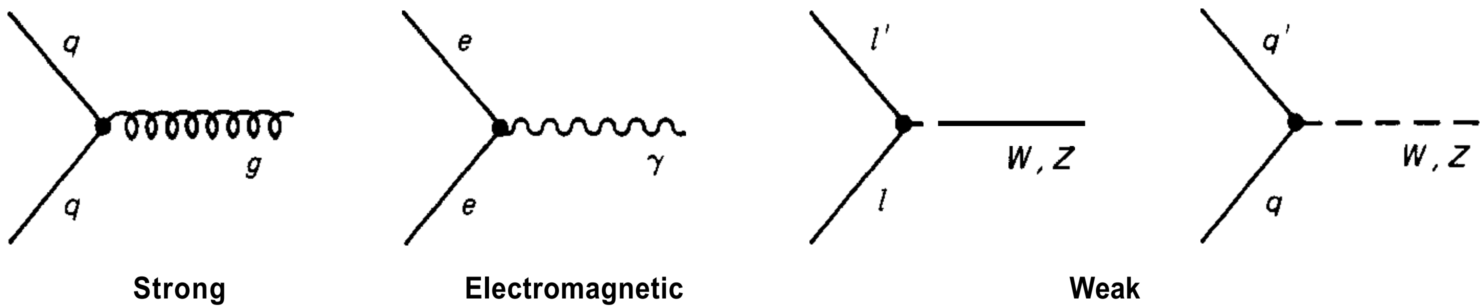
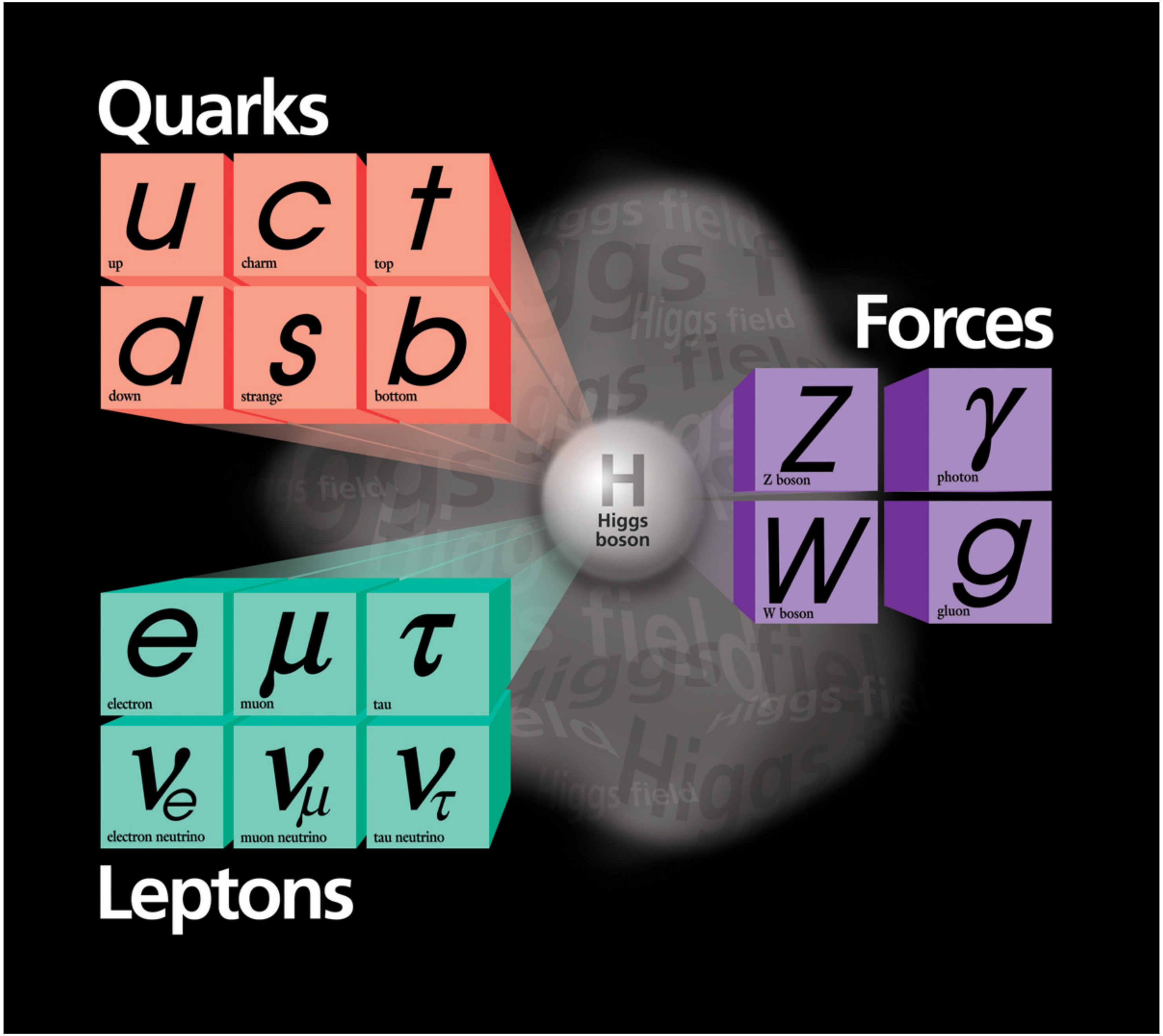


Q: why a proton does not decay to a neutron ?
Q: Why the electron is stable ?
Q: Why the proton is stable ?
Q: are the positron and the antiproton stable ?
Q: Why there we don't observe mu—>e gamma ?

Conservation laws

Q: why a proton does not decay to a neutron ?	Kinematics
Q: Why the electron is stable ?	no lighter lepton
Q: Why the proton is stable ?	no lighter baryon
Q: are the positron and the antiproton stable ?	no lighter anti-baryon
Q: Why don't observe mu—>e gamma ?	lepton flavour violation

Summary


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs
boson
Higgs field
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons