Elementary Particle Physics: theory and experiments

1. **Introduction: highlights of last 100 years**
2. **Accelerators and experiments (mostly LHC)**
3. **Detectors**
4. **Measurements in Standard Model Physics**
5. **Discovery and properties of the Higgs boson**
6. **Searches for New Physics**
7. **Run II of LHC: goals and prospects**

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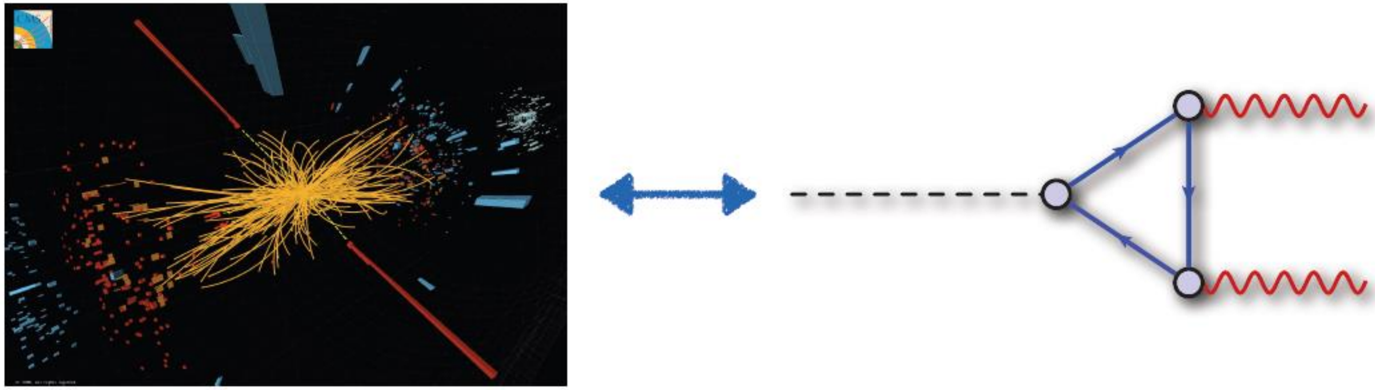
Elementary particle physics

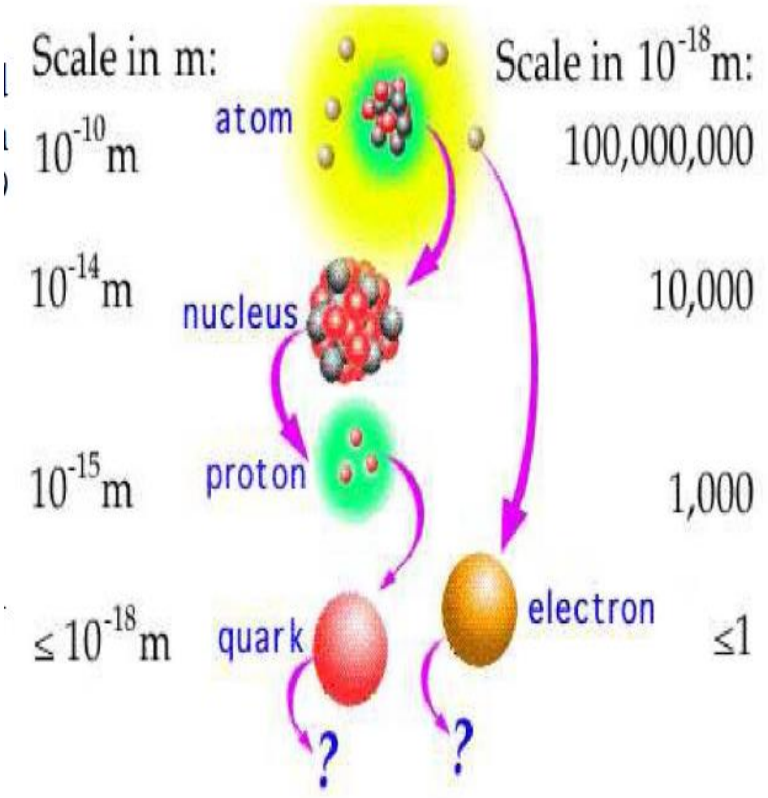
This course will introduce the Standard Model of particle physics and both theoretical foundations and experimental techniques. **Main aim is to introduce phenomenology side of particle physics.**

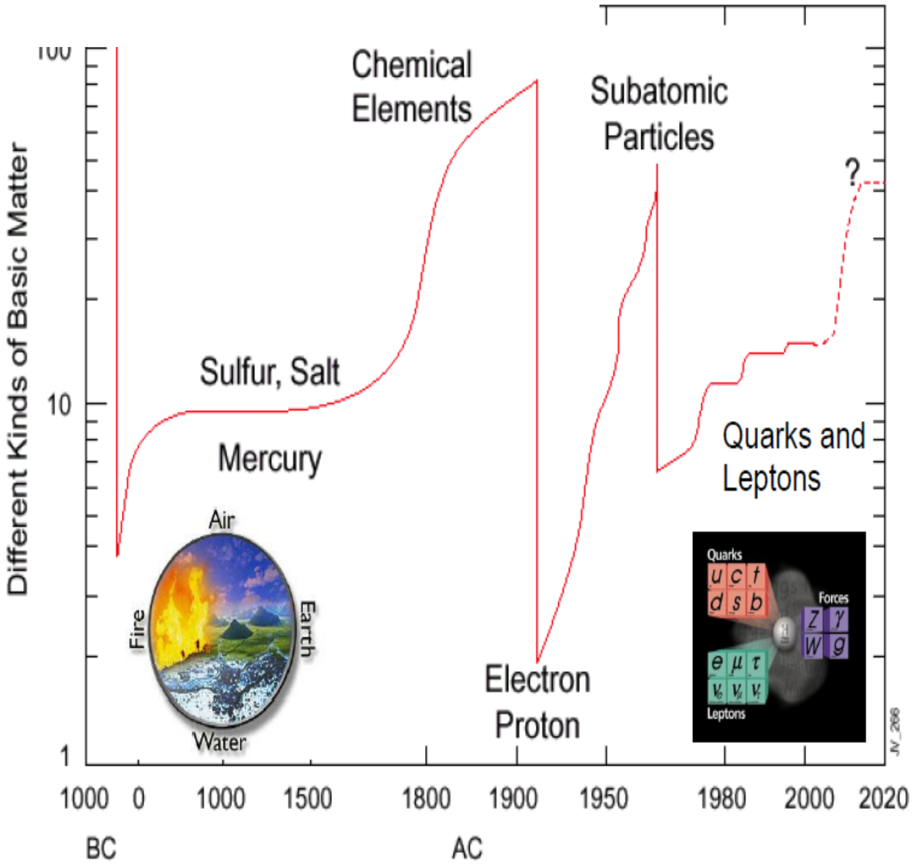
- Most of the presented experimental material will come from up-to-date measurements at LHC experiments.
- The theoretical foundations will follow book by **D. Griffiths, „Introduction to Elementary Particles”**.

When preparing those slides, I have borrowed some material from lectures or courses by: F. Krauss, C. Williams, P. Bechtle, R. Otario, Ch. Sanders, and others.



Constituents of matter along History

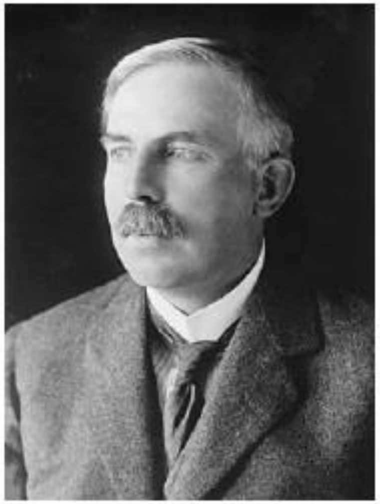




Early fundamental particles

The earlies fundamental particle discovery was the electron, by J. J. Thomson in 1987

Followed by the discovery of proton by Rutherford in 1917



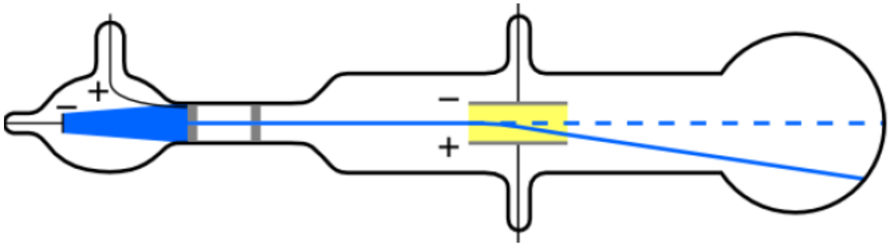
The atomic model was completed in 1932 when Chadwick discovered the neutron.

The Electron

Observation: 1897

- Constituents of cathode rays deflected by electric field
- Constituents of cathode rays deflected by magnetic fields + heating of thermal junction -> first mass/charge ratio
- Higher precision of mass/charge from comparing deflection by electric and magnetic field

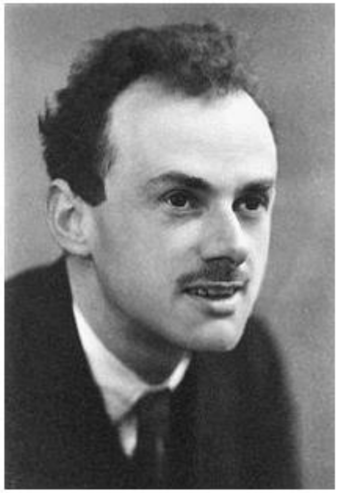
Joseph J. Thomson, *1856, †1940 (NP 1906)



Quantum Mechanics

Solvay Physics Conference 1927: Electrons and Photons
29 attendants, 17 became Nobel Prize winners

Anti-particles

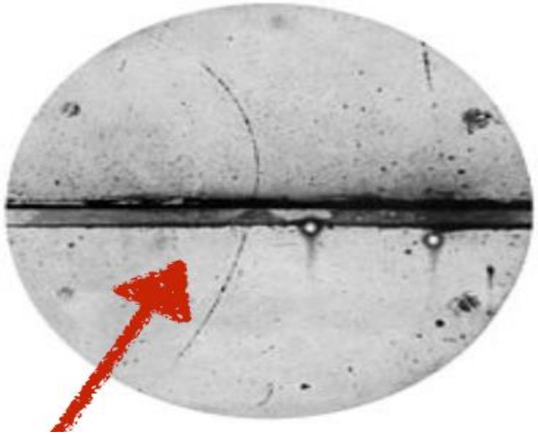


- This was achieved by **Dirac** in 1927,

$$i\gamma^{\mu}\partial_{\mu}\psi = m\psi$$

It permits (demands) solution with negative energy!

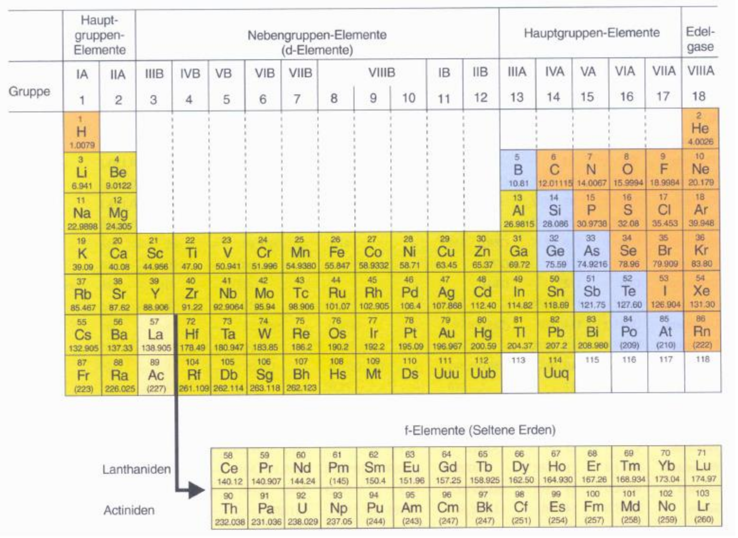
- Dirac proposed that the vacuum is made up of a „sea” with energy electrons
- What in 1930 was a huge issue for Dirac’s equation became in 1931 its greatest's triumph, **Andersen** discovered the positron



Curvature (mass to charge ratio) matches that of electron but with opposite charge!

The strong force

What force binds protons and neutrons together to form the elements of the periodic table and just the world around us



	Hauptgruppen-Elemente		Nebengruppen-Elemente (d-Elemente)										Hauptgruppen-Elemente					Edelgase
	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
Gruppe	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	1 H 1.0079																	2 He 4.0026
	3 Li 6.941	4 Be 9.0122											5 B 10.81	6 C 12.01115	7 N 14.0067	8 O 15.9994	9 F 18.9984	10 Ne 20.179
	11 Na 22.9898	12 Mg 24.305											13 Al 26.9815	14 Si 28.086	15 P 30.9738	16 S 32.08	17 Cl 35.453	18 Ar 39.948
	19 K 39.09	20 Ca 40.08	21 Sc 44.956	22 Ti 47.90	23 V 50.941	24 Cr 51.996	25 Mn 54.9380	26 Fe 55.847	27 Co 58.9332	28 Ni 58.71	29 Cu 63.45	30 Zn 65.37	31 Ga 69.72	32 Ge 75.59	33 As 74.9216	34 Se 78.96	35 Br 79.909	36 Kr 83.80
	37 Rb 85.467	38 Sr 87.62	39 Y 88.906	40 Zr 91.22	41 Nb 92.9064	42 Mo 95.94	43 Tc 98.906	44 Ru 101.07	45 Rh 102.905	46 Pd 106.4	47 Ag 107.868	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
	55 Cs 132.905	56 Ba 137.33	57 La 138.905	72 Hf 178.49	73 Ta 180.947	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.2	83 Bi 208.980	84 Po (209)	85 At (210)	86 Rn (222)
	87 Fr (223)	88 Ra 226.025	89 Ac (227)	104 Rf 261.109	105 Db 262.114	106 Sg 263.118	107 Bh 262.123	108 Hs	109 Mt	110 Ds	111 Uuu	112 Uub	113	114 Uuq	115	116	117	118

f-Elemente (Seltene Erden)

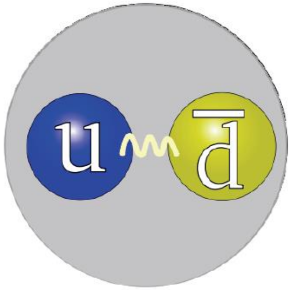
Lanthaniden	58 Ce 140.12	59 Pr 140.907	60 Nd 144.24	61 Pm (145)	62 Sm 150.4	63 Eu 151.96	64 Gd 157.25	65 Tb 158.925	66 Dy 162.50	67 Ho 164.930	68 Er 167.26	69 Tm 168.934	70 Yb 173.04	71 Lu 174.97
Actiniden	90 Th 232.038	91 Pa 231.036	92 U 238.029	93 Np 237.05	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (254)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

We know it has to be a force which is considerably stronger than the electric force since atoms made of 10’s-100’s protons stick together

We also know, from daily experience that a long distance (~> a few 10^{-13} m) we do not experience the nuclear force

The mesons

Yukawa was the first to propose a model of strong force, in 1934. Proposed a new field, which mediated the interaction between the proton and the neutron



Since the force is short range, Yukawa made the mediator heavy, so it cannot propagate to long distances

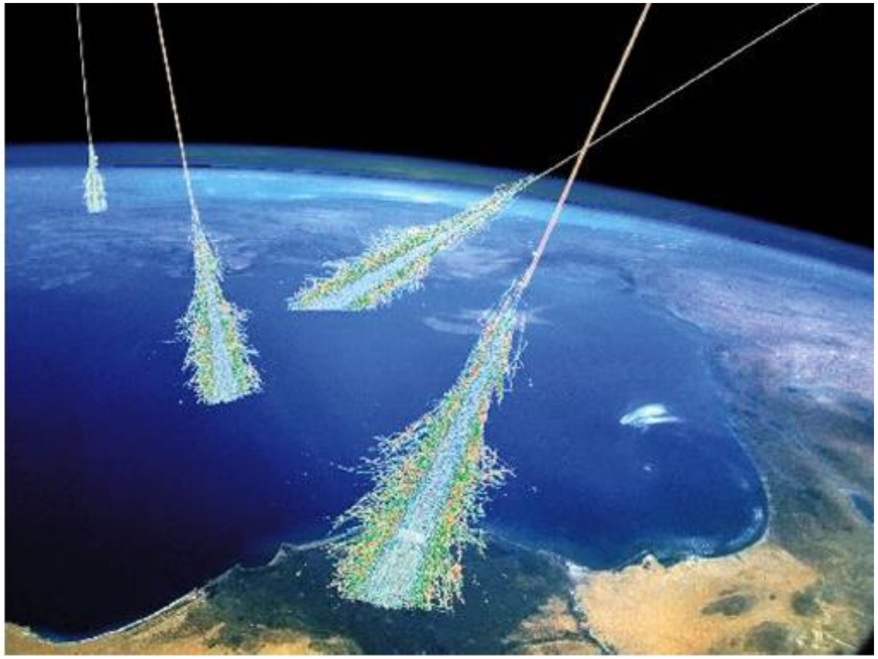
Yukawa reasoned this bosonic meson must be about 300 heavier than electron

The proton and neutron are examples of baryons which are fermionic

Pion discovery?

Around this time, one of the primary particle physics laboratories was the study of energetic particles hitting the earth's upper atmosphere.

In 1937 Anderson (again) and Neddermeyer discovered a particle which appeared consistent with Yukawa's meson.



This particle has a mass of around 200 times the electron.

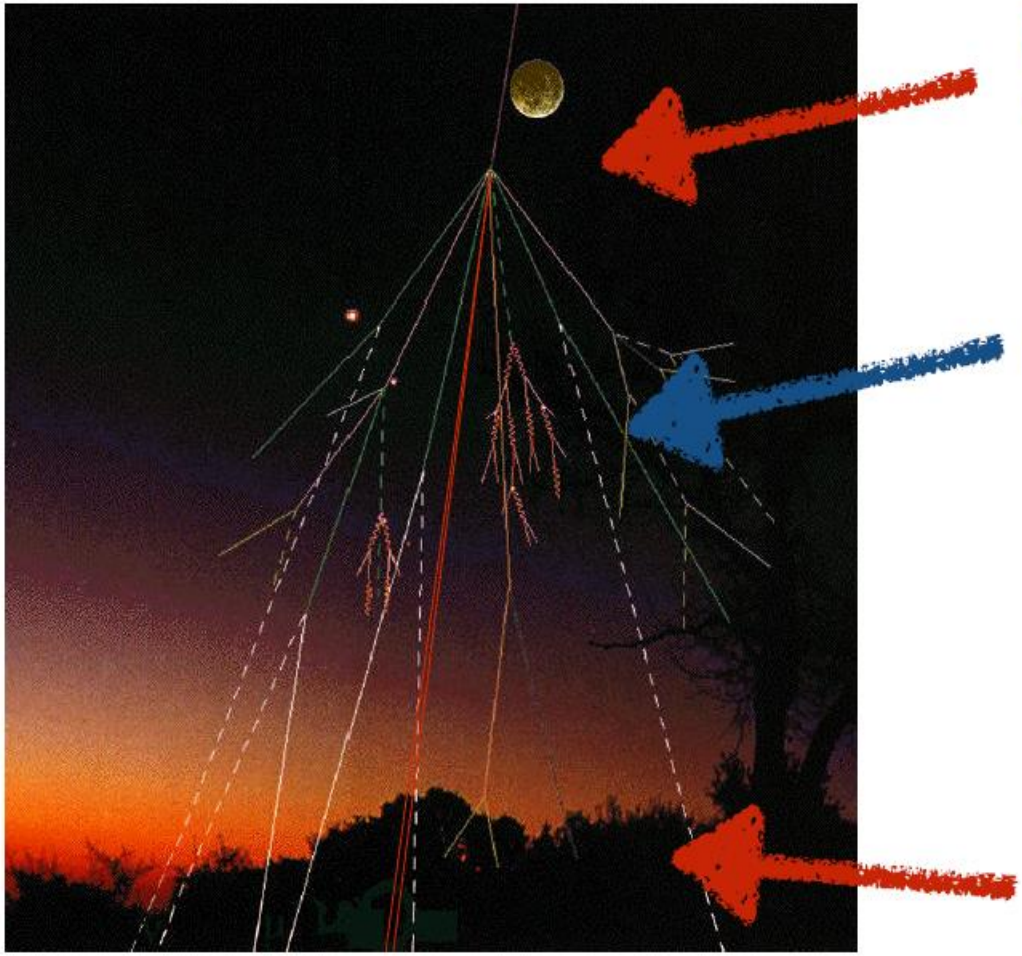
A puzzle

The problem with this new particle was that it did not interact strongly enough with nuclei to be the carrier of the strong force.

In fact, what was discovered was the muon, a heavier copy of the electron.

The actual pion (lightest mezon) was found in 1947 by Powel

The muon



Pions produced in initial cosmic ray interaction

Pions decay, e.g. through

$$\pi^- \to \mu^- + \overline{\nu}$$

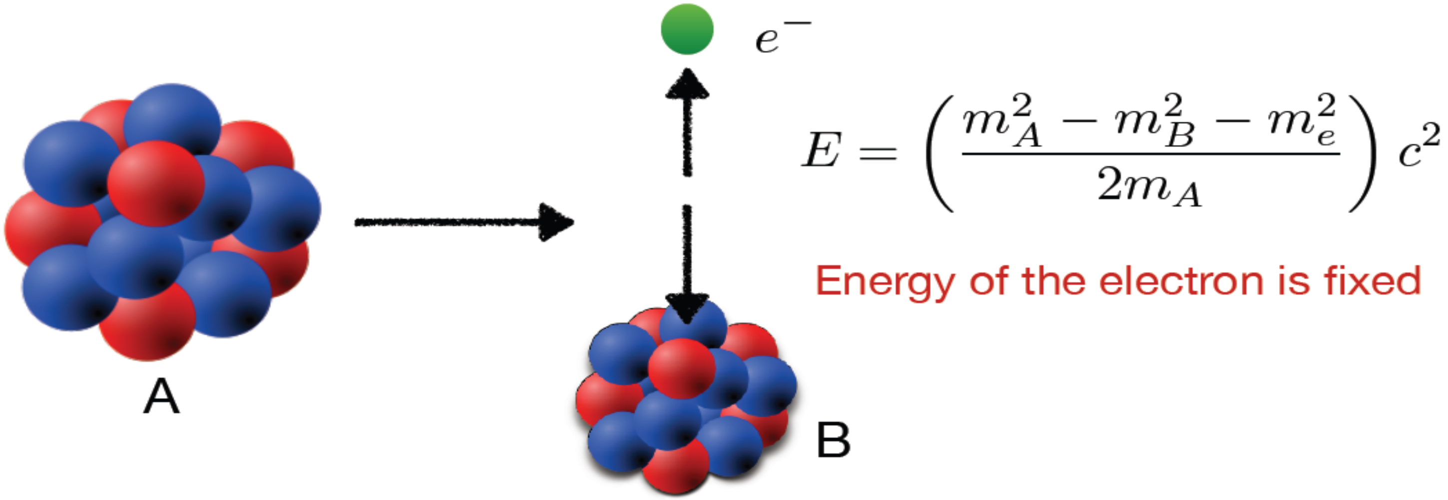
At lower altitude we detect mostly muons.

A puzzle

The discovery of the muon was completely unexpected.

The world of leptons was becoming increasingly more interesting …

Radioactive decays provided a mystery, if a heavy nuclei A decays at rest into an electron and a lighter nuclei B then the conservation of energy fixes the energy of the electron

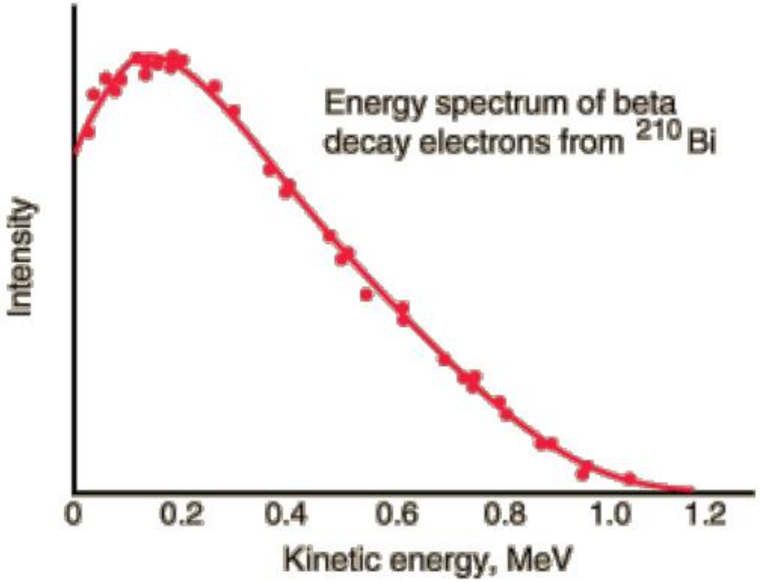


$$E = \left(\frac{m_A^2 - m_B^2 - m_e^2}{2m_A} \right) c^2$$

Energy of the electron is fixed

Neutrinos

This is not what is actually observed!



G. J. Neary, Roy. Phys. Soc. (London), A175, 71 (1940).

Pauli proposed that a new, very weakly interacting neutral particle is present, and restores the conservation of energy.

Fermi constructed a beautiful description of beta decay which incorporated Pauli’s neutrino in 1933.

Neutrinos

Neutrinos appear everywhere

Beta decay	$n \rightarrow p + e^{-} + \overline{\nu}$
Pion decays	$\pi^{-} \rightarrow \mu^{-} + \overline{\nu}$
Muon decay	$\mu^{-} \rightarrow e^{-} + 2\nu$

This is all nice theoretically, but is there any experimental evidence?

Are neutrinos and anti-neutrinos different particles?

Neutrinos

In the 1950’s **Cowan** and **Reines** used the inverse beta decay

$$\overline{\nu} + p^+ \rightarrow n + e^+$$

To conclusively prove the existence of anti-neutrinos

The non-observation of process

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

proved that neutrinos and anti-neutrinos are fundamentally different particles

Frederick Reines (left) and Clyde L. Cowan, Jr. with the control equipment used in their first tentative observations of the neutrino at Hanford, Washington, in 1953. Their definitive detection of the (anti) neutrino was performed at Savannah River, Georgia, three years later. (Courtesy General Electric Co.)

Lepton Number

The non-observation of the crossed process was theoretically expected based upon the idea of Lepton number conservation.

Matter particles (electrons, muons, neutrinos) are assigned lepton-number L=+1, whilst anti-mater particles (positrons, anti-muons and anti-neutrinos) are assigned L=-1, all other particles have L=0

Lepton number conservation then ensures that both LHS and RHS of reactions have the same total Lepton number.

$$\overline{\nu} + p^{+} \rightarrow n + e^{+}$$

L : +1 +0 => 0 + 1

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

L : +1 +0 => 0 - 1

Lepton Number

Lepton number conservation allows us to rewrite the decay of muon

$$\mu^- \rightarrow e^- + 2\nu \longrightarrow \mu \rightarrow e + \nu + \overline{\nu}$$

What about?

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

$Br(\mu^+ \rightarrow e^+\gamma) < 5.7 \times 10^{-13}$ MEG experiment in PSI

Lepton Number

The lack of muon decays to electron and a photon suggests a conservation law of „mu-iness"

But what about regular muon decays?

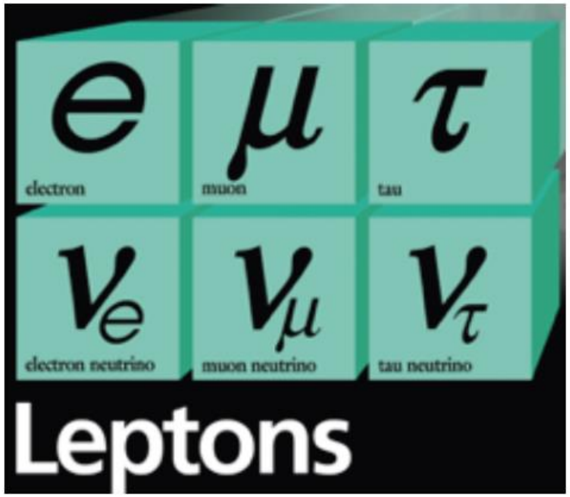
$$\mu \rightarrow e + \nu + \overline{\nu}$$

There must be (at least) two types of neutrinos

$$\mu^- \rightarrow e^- + \nu_\mu + \overline{\nu}_e$$

The Lepton Family

We know now that there are 3 families of leptons, the tau lepton was discovered in 1975 and tau neutrino in 2000 (DONUT experiment)



$$m_e = 0.511 \quad \text{MeV}$$

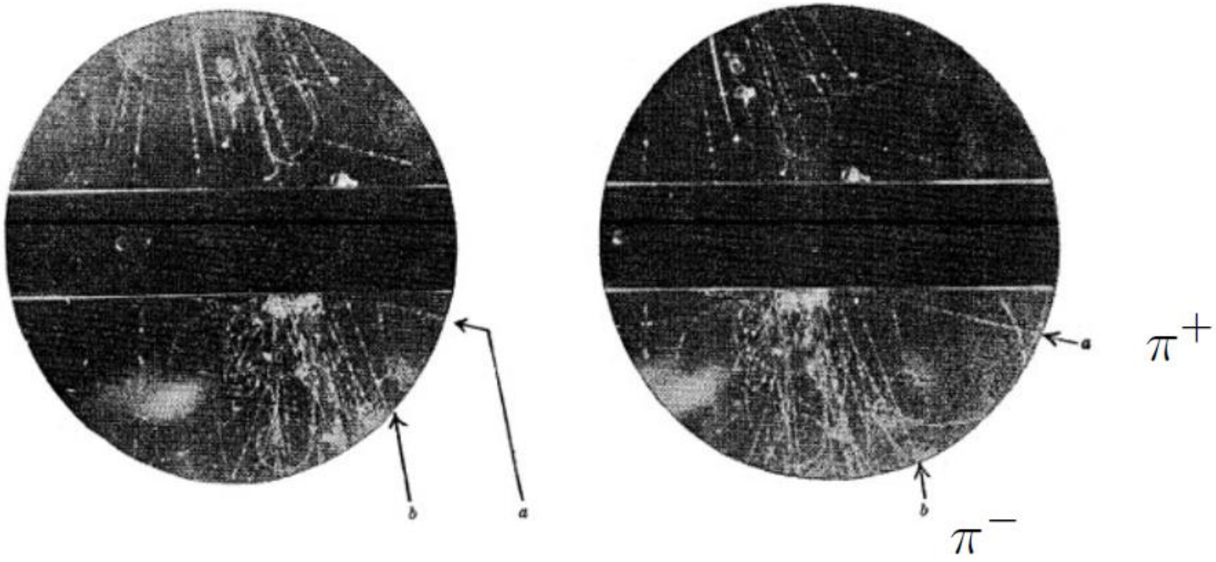
$$m_\mu = 105.7 \quad \text{MeV}$$

$$m_\tau = 1.78 \quad \text{GeV}$$

However in 1947 it was no idea „what for” are muons (**I. Rabi**)

The strange tide

http://www.nature.com/physics/looking-back/rochester/index.html



In December 1947, Rocheter and Butler observed a „strange” new particle in cosmic ray experiments.

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

The particle appeared to be a new type of meson!

The strange tide

The Kaon was not the last „strange” particle to be discovered, in 1950 Anderson (again!) discovered a new heavy baryon through its decay products.

$$\Lambda \to p + \pi^-$$

How do we know this is a Baryon?
Similarly why are we here?

$$p \to e^+ + \gamma$$

Or

$$p \to e^+ + \gamma + \nu_e$$

These are pretty catastrophic processes for the Universe.

Baryon Number

In a similar fashion to what we saw for leptons, we introduce the concept of baryon number conservation

Proton and neutrons have a Baryon number of +1 (anti-baryons have a Baryon number of -1)

There is no corresponding meson number conservation, for example we already now how pions decay

$$\pi^- \rightarrow \mu^- + \overline{\nu}$$

Baryon number thus give a mechanism to quantify whether hadrons are baryons, or mesons, based on the production and decay mechanism, and baryon number conservation (you can use spin too, baryons are fermions, mesons are bosons).

The strange particles

The new strange particles are indeed „strange”

- **They are copiously produced in energetic collisions (with timescales around 10^{-23} seconds). But relatively long-lived, with lifetimes around 10^{-10} second.**
- This suggests that maybe there is different production mechanism and decay mechanism (i.e. two separate forces)
- **This is further backed up by noting that strange particles are produced in pairs e.g.**

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

- **But we can never singly produce a strange particle**

$$\pi^- + p \not\rightarrow \pi^+ + \Sigma^-$$

The weak force and strangeness

- All this suggests yet another quantum number, strangeness, which is conserved by the strong nuclear force, but not by the ***weak*** force.
- The **K's** have strangenes S=+1 and the **∑** has S=-1, ordinary matter has S=0.
- The strong and electromagnetic force conserve strangeness, but the weak force doesn't which allows strange particles to decay.

$$\Sigma^+ \to p^+ + \pi^0$$

- The introduction of a new force should not be surprising, we know that neutrinos, exist, but they are a) not charged, b) not strongly interacting, so one expect some new type of force, this is indeed the same weak force we see above.

We are around 1950'ties

- We learned that there were strange hadrons, which are pair produced in strong interactions, but decay via a new weak force.
- On the other hand, there are some hadrons, which are not strange, and decay via the strong force, for example lifetime ratio below:

Not strange

$$m_\Delta = 1232 \quad \mathrm{GeV}$$

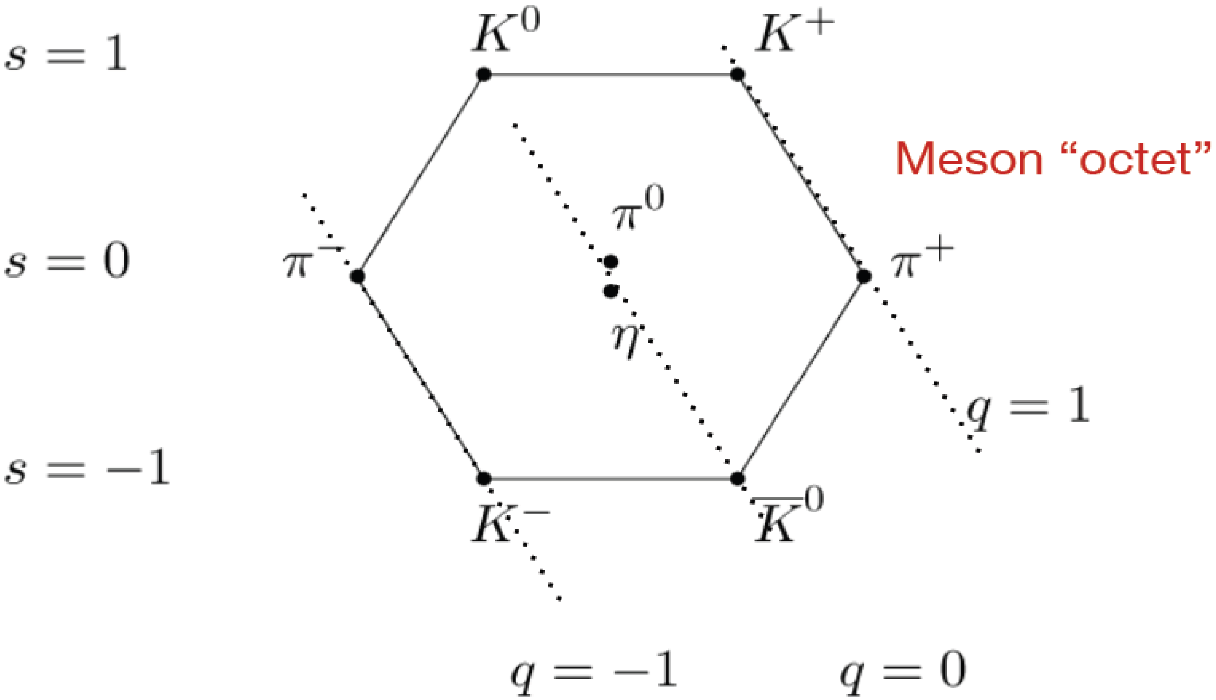
$$\frac{\tau(\Delta \to n + \pi)}{\tau(\Sigma \to n + \pi)} \approx \frac{10^{-23}}{10^{-10}}$$

$$m_\Sigma = 1189 \quad \mathrm{GeV}$$

Strange

- We want to understand this better: **The Quark Model**

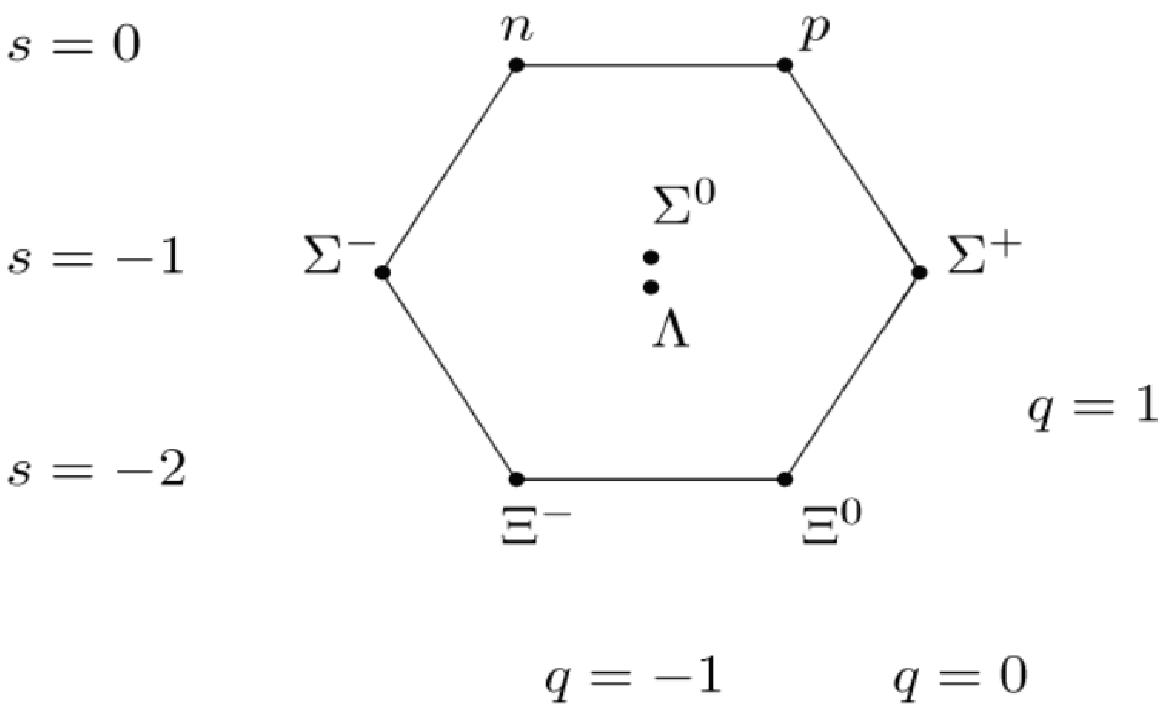
The „Eightfold way”



The first person who made significant progress on forming a „periodic table” for hadrons was Murray Gell-Mann   1961

The mesons can be grouped into the octed, based on charge and strangeness

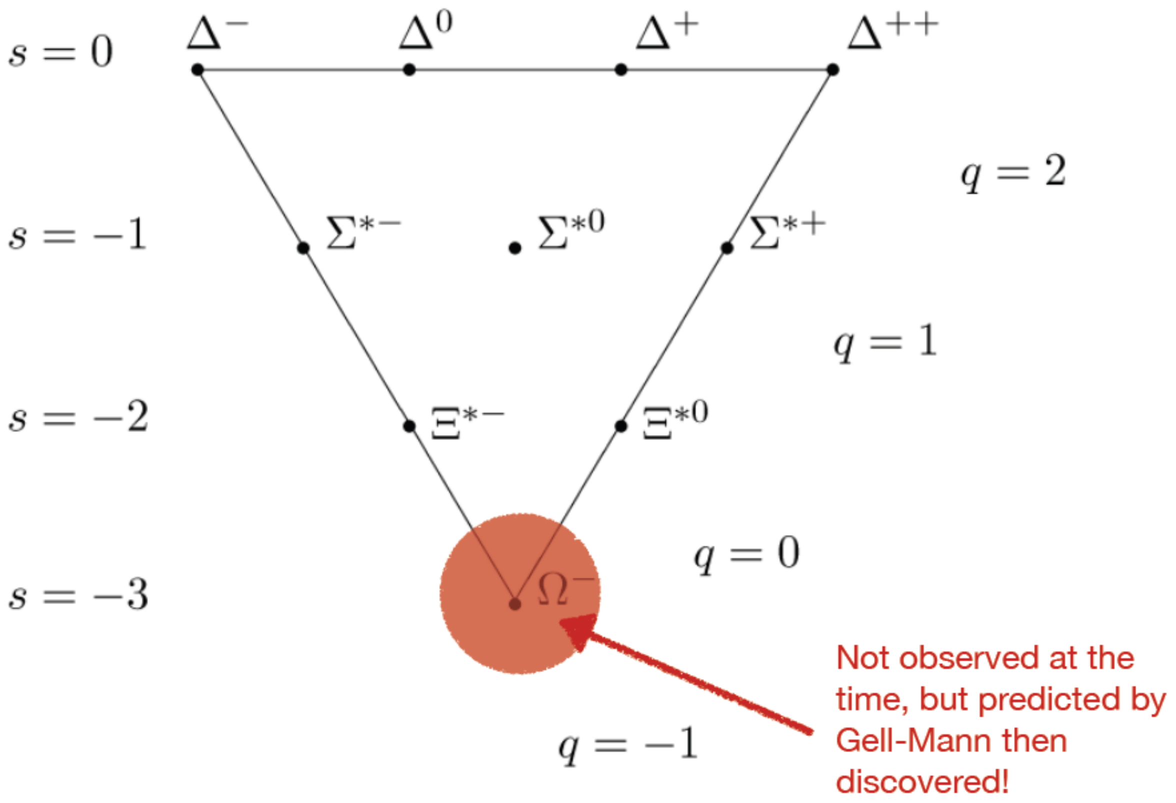
The „Eightfold way”



A similar octed appears for baryons, which includes also our friends: p and n

(note the shift in scale for the strangeness)

More baryons

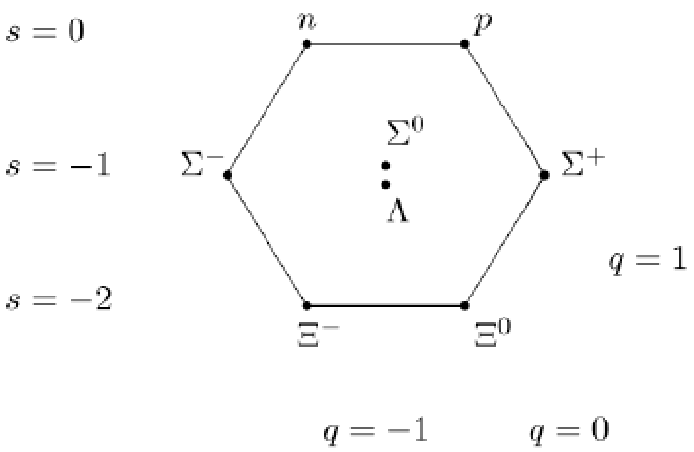


Not observed at the time, but predicted by Gell-Mann then discovered!

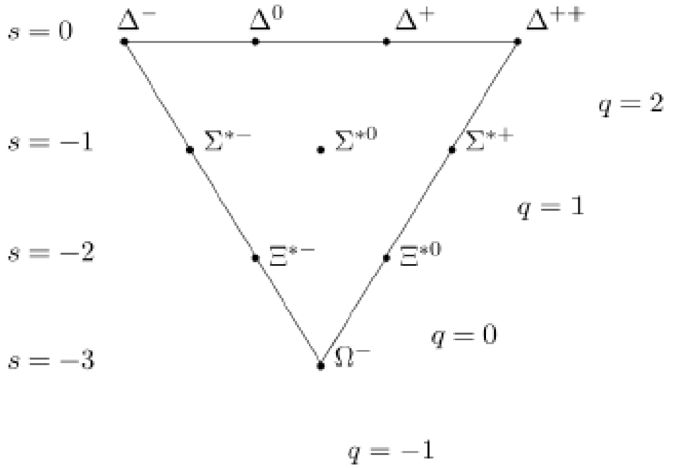
Nonet is not the only structure, spin 3/2 baryons form a decoupled.

The „Eightfold Way”

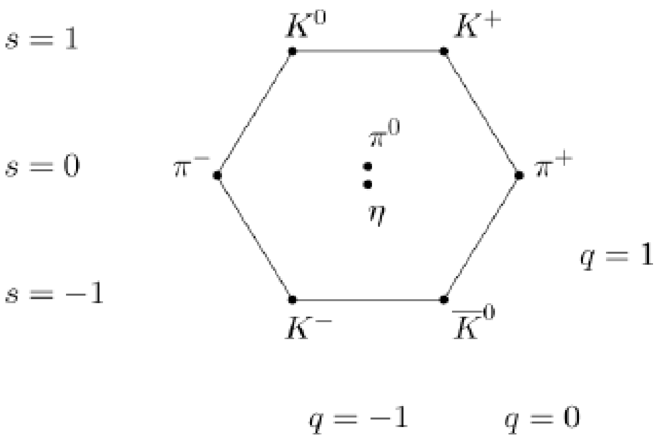
Baryon octet



Baryon decuplet



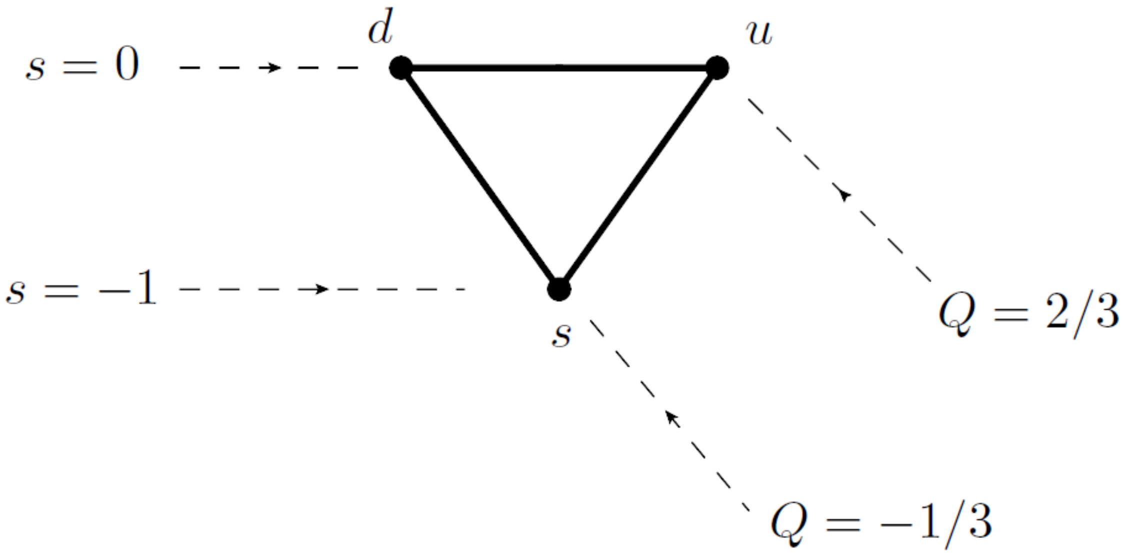
M. Gell-Mann
(NP 1969)



Meson octet

- Ordering Mesons and Baryons in octets (spin 1/2) and decuplets (spin 3/2), according to quantum numbers (i.e. quark composition)
- Prediction of baryons Ω^- with three *s* quarks (observed in 1964)
  → Pauli's exclusion principle
  → new quantum number (color)
- Number of colors from hadronic to leptonic branching ratio of e^+e^- collisions

The Quark Model



In 1964 Gell-Mann proposed a model to explain observed in the hadron spectrum. He postulated that there are 3 quarks, with the quantum numbers shown above. Using these quarks and corresponding anti-quarks) he was able to reproduce the observed spectrum of hadrons.

The Quark Model

In the quark model the hadrons are constructed according to the following rules:

1) **Baryons are made of three quarks (qqq), anti-baryons are made of anti-quarks**

$p = uud$

$n = udd$

$\Omega^- = sss$

$\Sigma^{*+} = uus$

2) **Mesons are made of quark anti-quark pair.**

$\pi^+ = u\overline{d}$

$K^+ = u\overline{s}$

Problems for the Quark Model

The quark model has a serious flaw as it currently stands, namely it predicts:

$$\Delta^{++}_{3/2} = u_{\uparrow}u_{\uparrow}u_{\uparrow}$$

Worse still, such a doubly charged spin 3/2 baryon was observed by Fermi in 1951, and lives in our decoupled

As it stands our states are completely symmetric indistinguishable quantum state made up of spin ½ fermions, and is in complete violation of our understanding of spin statistics

A second less catastrophic problem, is the lack of existence of qq and other allowed states. Foe example n uu charge 4/3 meson has ever been observed, but there is no reason to not construct it in our simple quark model.

Color: the „charge” of a strong force

We solve both of these problems with the introduction of the color charge.

We re-write the wave function as follows,

$$\Delta^{++}_{3/2} = u^{R}_{\uparrow} u^{G}_{\uparrow} u^{B}_{\uparrow}$$

We introduce three color charges, and assign a different one to each up quark, now the particles ar distigushable and the spin-statistics theorem is satisfied.

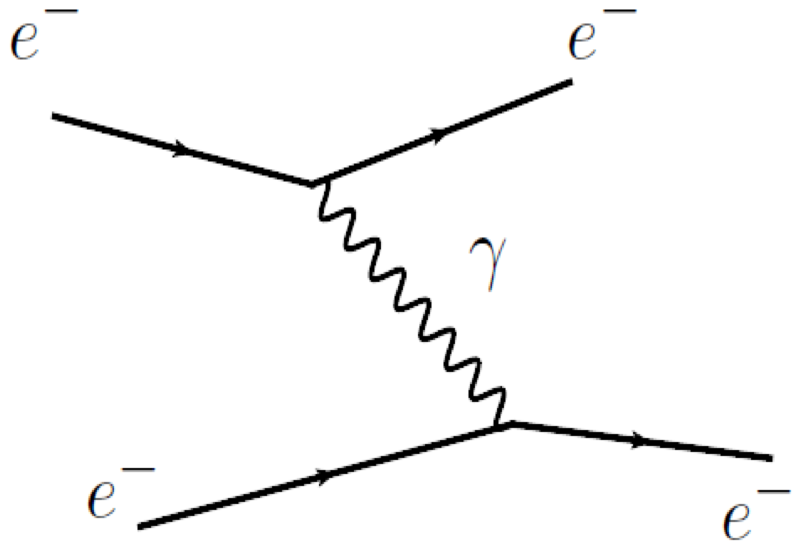
Color: the „charge” of a strong force

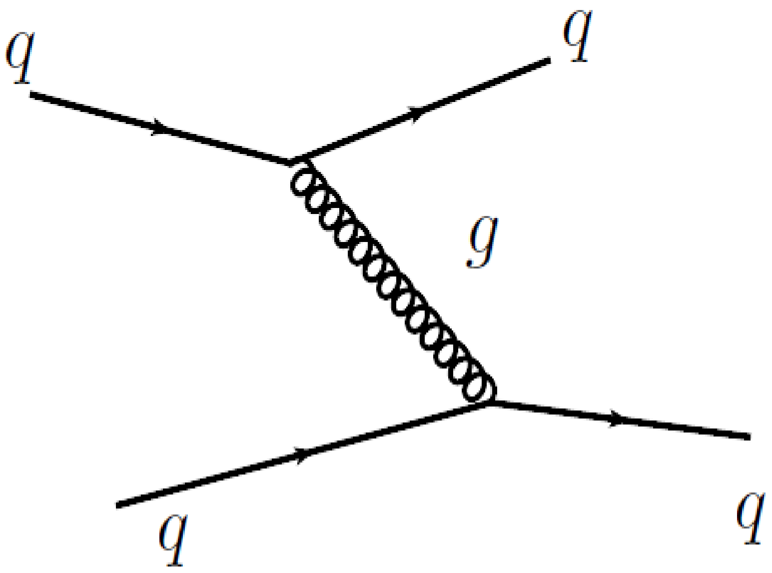
Since we don’t „see” color like we do charge, we also enforce that all observed hadrons are „white”, i.e. color neutral combinations

Color neutral (white) combinations are given by either combining RGB, a=ro a color wit its anti-color (in a meson) e.g. R $\overline{\text{R}}$

$$p = \text{“}RGB\text{”} \quad n = \text{“}RGB\text{”} \quad \pi = \text{“}R\overline{R} + G\overline{G} + B\overline{B}\text{”}$$

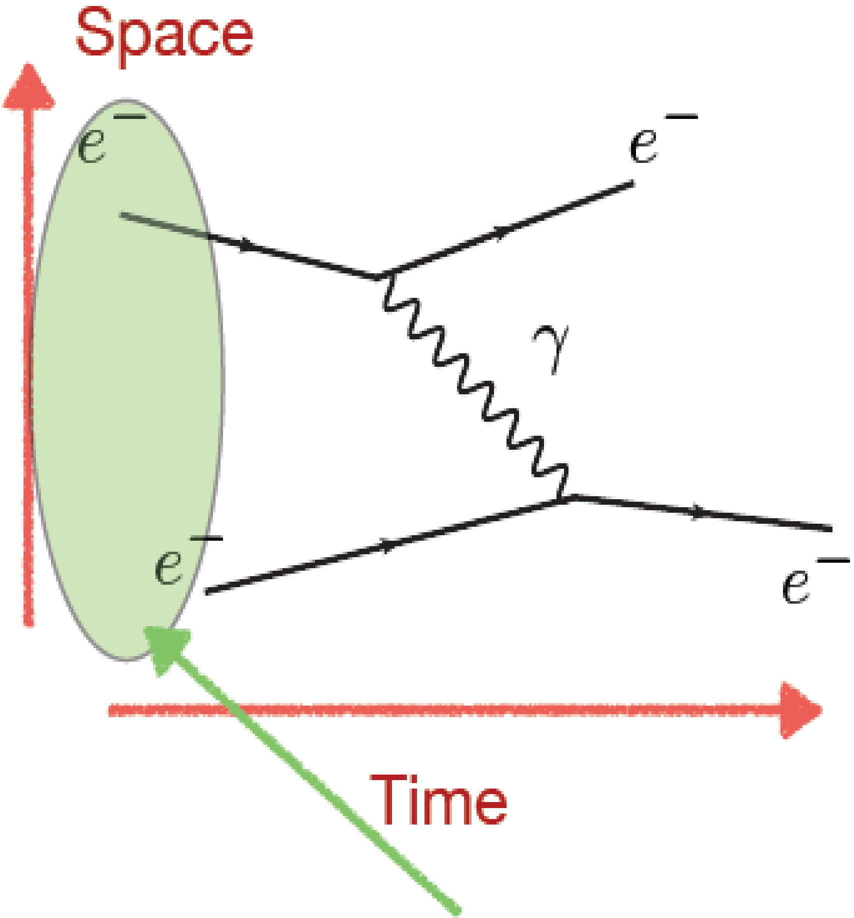
The gluon: the „photon” of the strong force

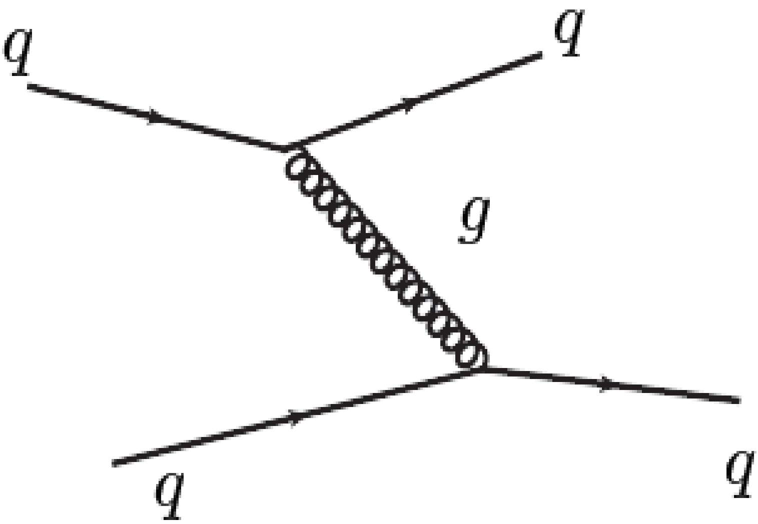




Here we discuss it only heuristically, I will come back to it latter

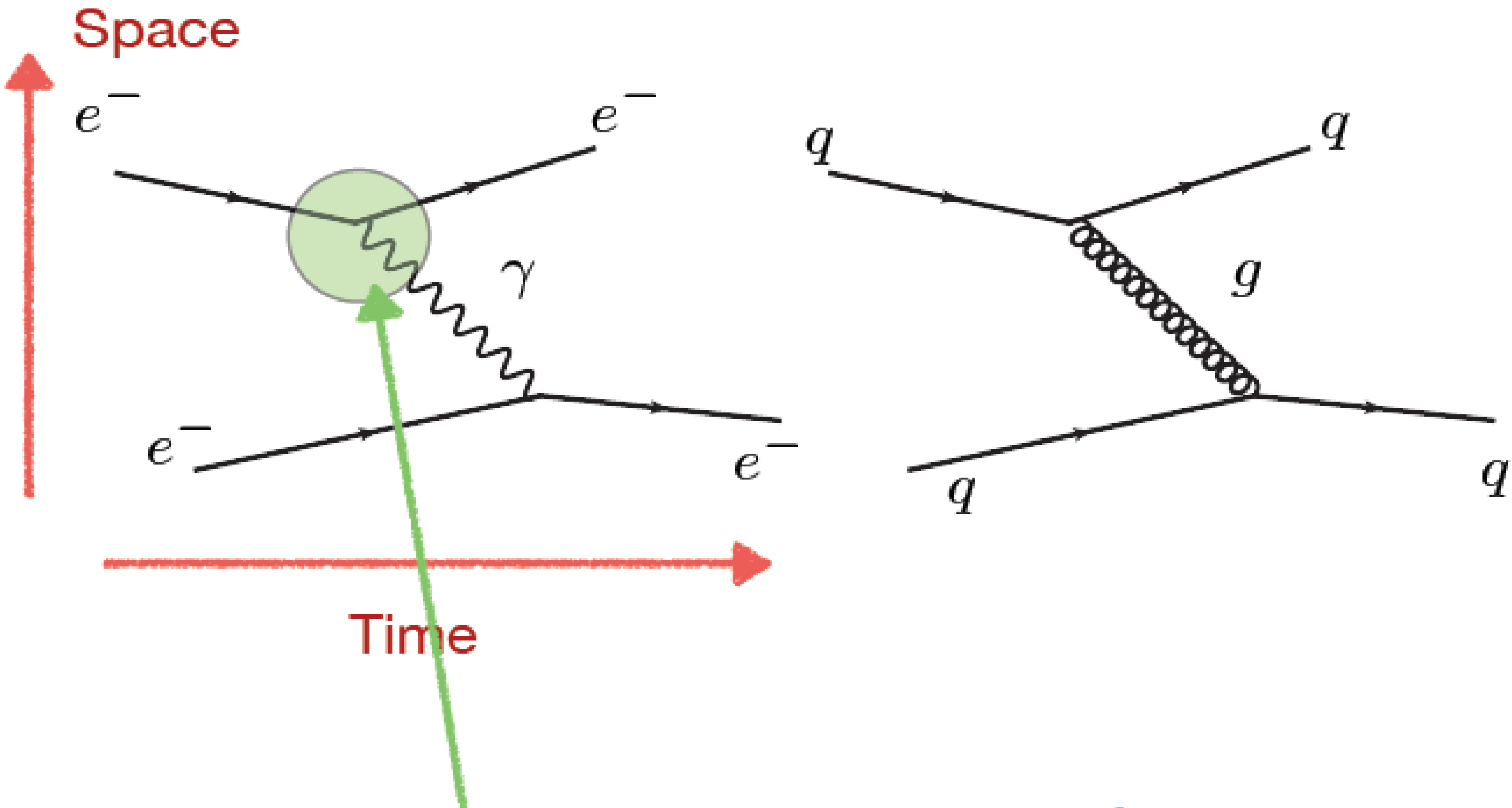
The gluon: the „photon” of the strong force





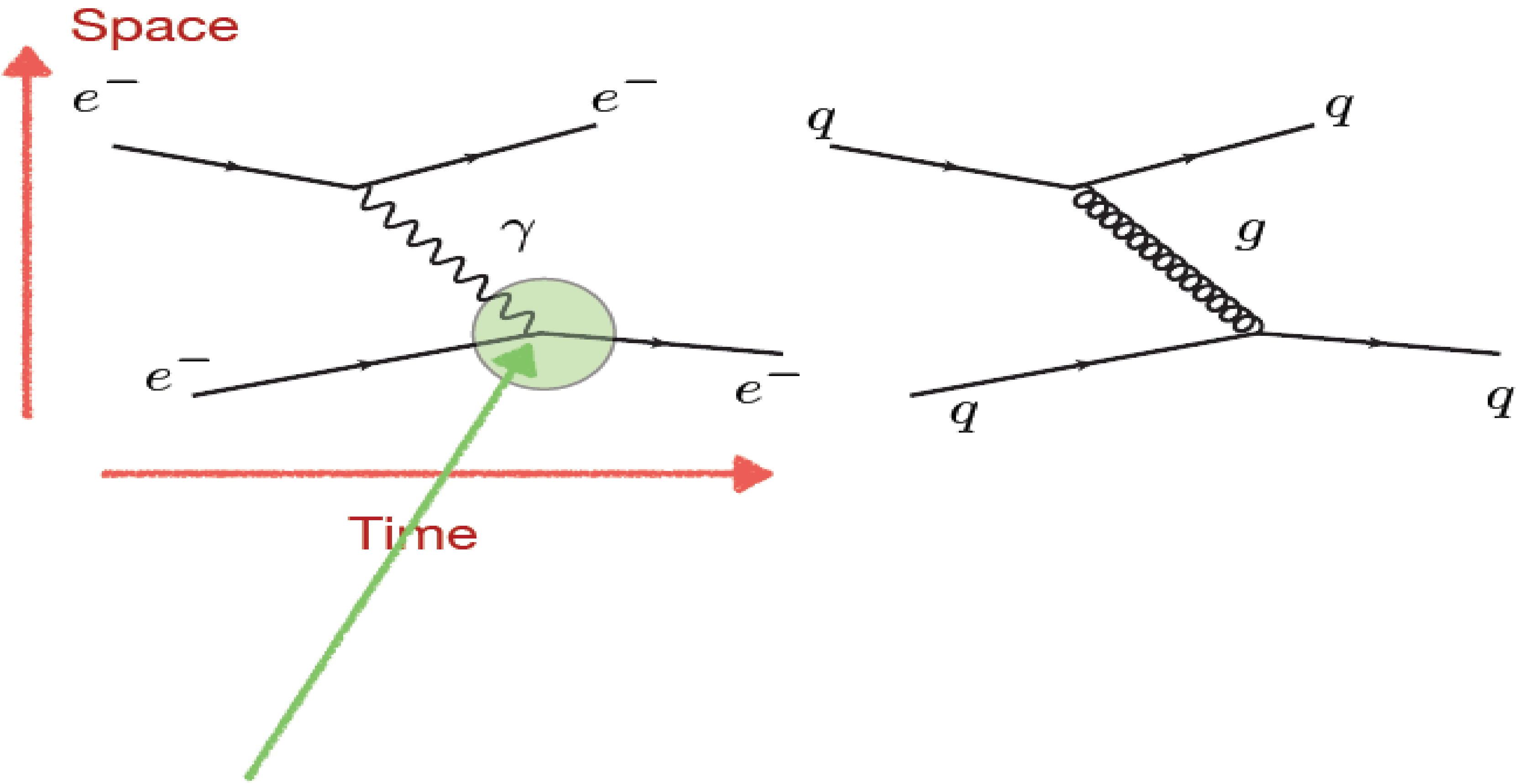
At t=0 two electrons are incoming.

The gluon: the „photon” of the strong force



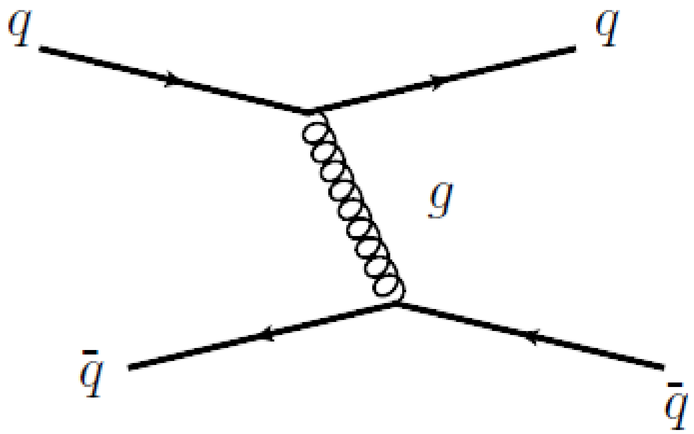
Then at some later time one of the electrons emits a “virtual” photon (this is completely quantum with no classical analog)

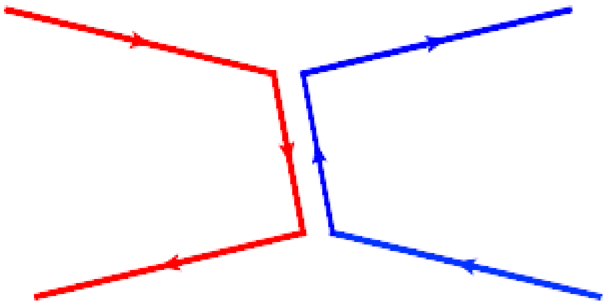
The gluon: the „photon” of the strong force



Finally the second electron, reabsorbs the photon, and feels the Coulomb repulsion from the first electron.

The gluon: the „photon” of the strong force



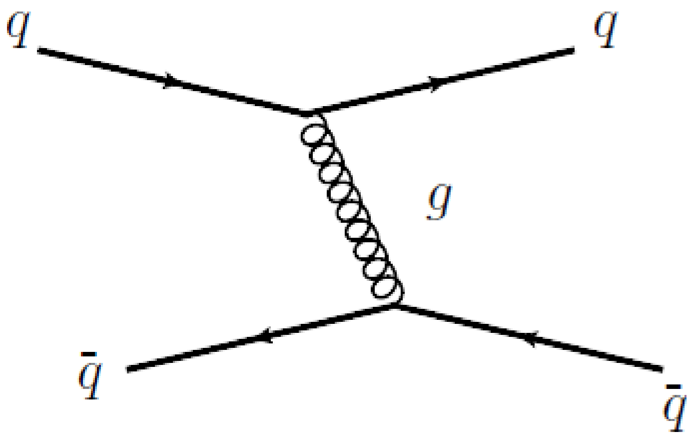


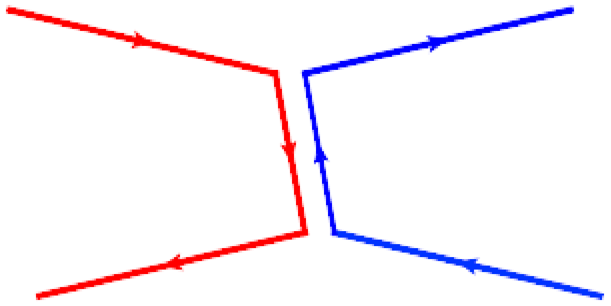
There must be an equivalent messenger of the strong force. Since it is responsible for „gluing” quarks together inside hadrons, we call it the gluon.

However, unlike the case of electron scattering, there are multiple color charges that interact with each other. In the above a red quark scatter off an anti-red anti-quark, producing new blue quark/anti-quark in the final state.

Therefore in order to mediate the strong force, it is clear that the gluon itself must be colored, and it carriers two indices.

The gluon: the „photon” of the strong force





Simple counting suggest there should be nine combinations of gluons pairings

$$R\bar{R},\ R\bar{G},\ R\bar{B},\ B\bar{R},\ B\bar{G},\ B\bar{B},\ G\bar{R},\ G\bar{G},\ G\bar{B}$$

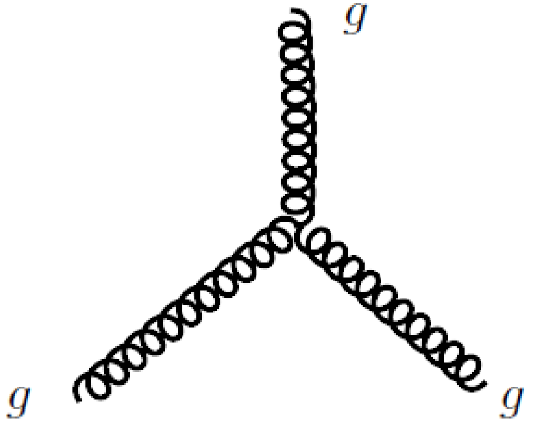
However, we already know that the combination

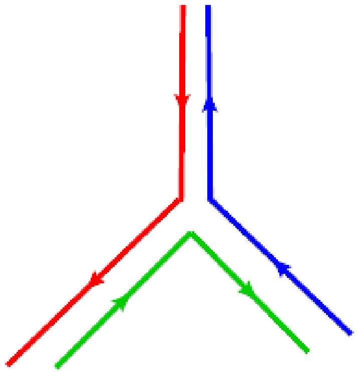
$$R\bar{R} + B\bar{B} + G\bar{G}$$

Is a color singlet (this is a color charge of a pion), so we can actually eliminate one color combinations from the basis.

Therefore ther are 8 gluons!

Self interactions of gluons





A further, fundamental difference between photons and gluons, is that gluons, which are charged under the strong force (i.e. are colored objects) can interact with themselves.

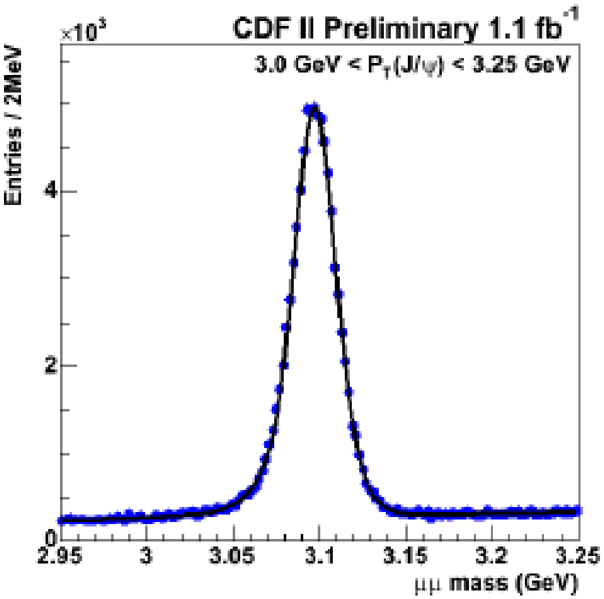
This results in dramatically different physics from electromagnetic interactions and ultimately leads to the bounding of nuclei together.

Theories, like electromagnetism, in which the boson mediator is not charged under the interaction are called Abelian, theories like the strong force, in which gluon boson itself carries the color charge, are called Non-Abelian

The J/Ψ discovery

Initially reaction to the quark model was mixed, its simplicity and predictivity was admired. But the inability to produce free quarks, and the ad hoc nature of the color interpretation were serious issues.

In 1974 the game changed with the discovery of a new very heavy meson (3 times heavier than the proton). This particle was (almost) simultaneously discovered at Brookhaven and SLAC



It was easy to incorporate this new meson into the quark model, by adding in a new heavy quark, the **charm quark**

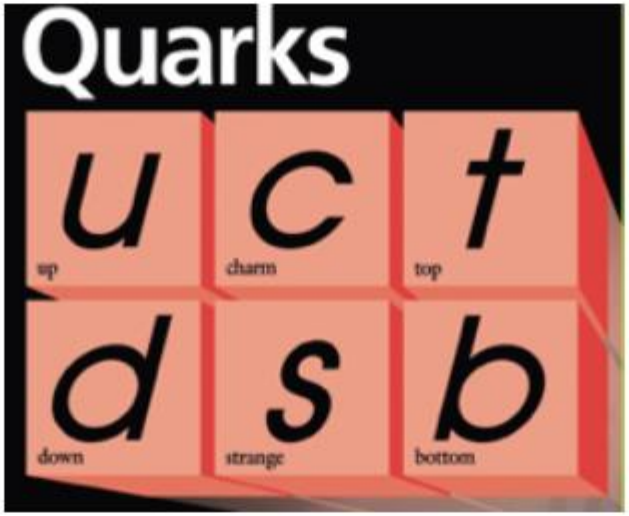
$$J/\Psi = c\bar{c}$$

The quark model then predicts many new baryons and mesons which contain charm quark

Completing the quark story

Since then two additional quarks have been discovered, the bottom quark (1977) and top quark (1995) were discovered at Fermilab.

The third generation of quarks are very heavy, the bottom quark has a mass around 5 x the mass of the proton, whilst the top quark has a mass around 175 times that of the proton!

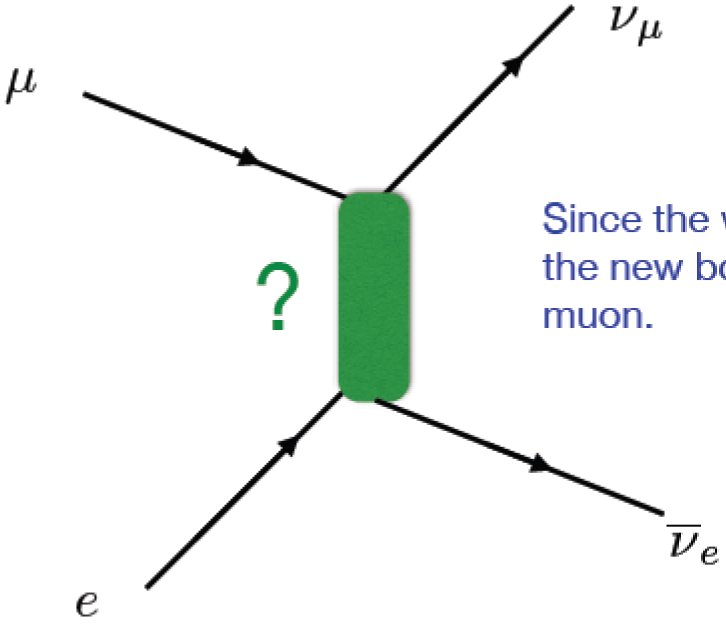


We still believe that quarks are fundamental and that Standard Model includes a fundamental particle heavier than a Gold nuclei!

Massive vector bosons

Fermi's theory for muon decay related the decay to a 4 fermion contact interaction.

However, we know that this is only true at low energies, we know that there has to be force carrying boson, like the photon and the gluon.



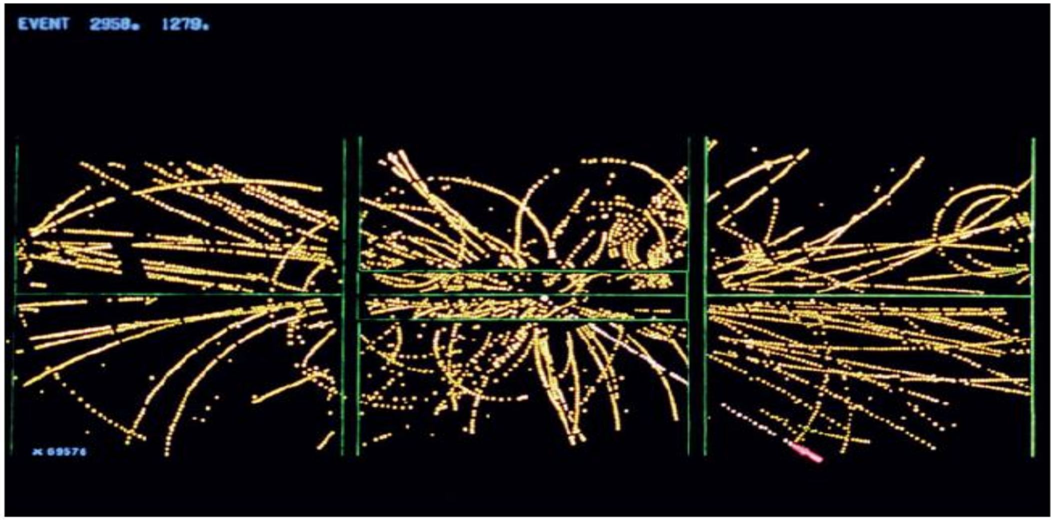
Since the weak force is short range, we expect the new boson to be much heavier than the muon.

The search for massive vector bosons, to mediate the weak force, was on!

The W and Z boson

The hunt for the W and Z bosons was finished in 1983, when they were discovered at CERN. The bosons are heavy, with masses,

$$m_W = 80.4 \quad \text{GeV} \qquad\qquad m_Z = 91.2 \quad \text{GeV}$$

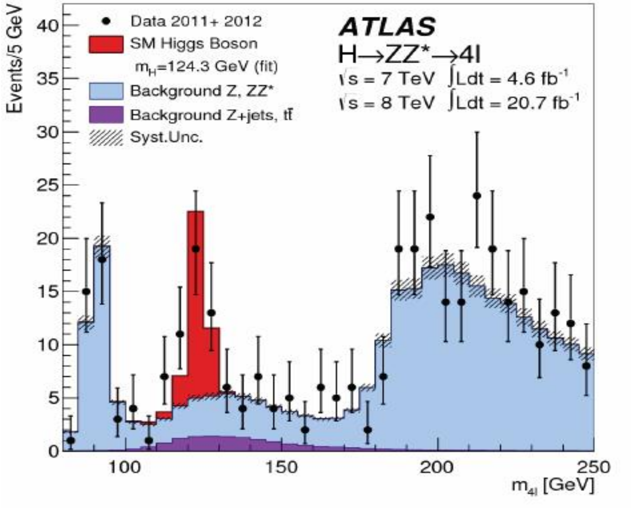


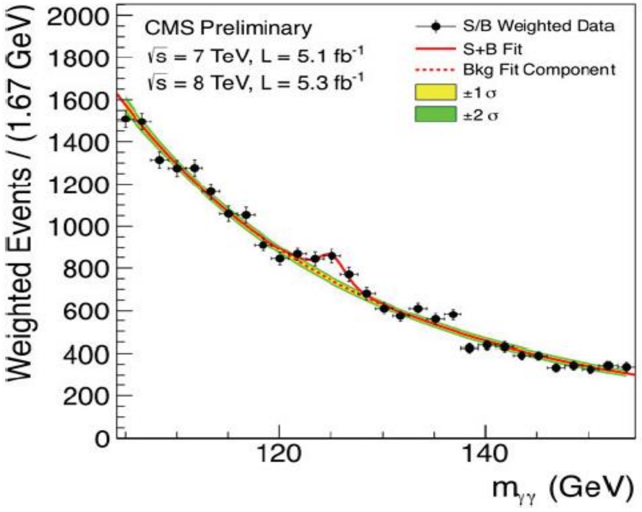
The Higgs boson

The final piece of the Standard Model was the Higgs boson.

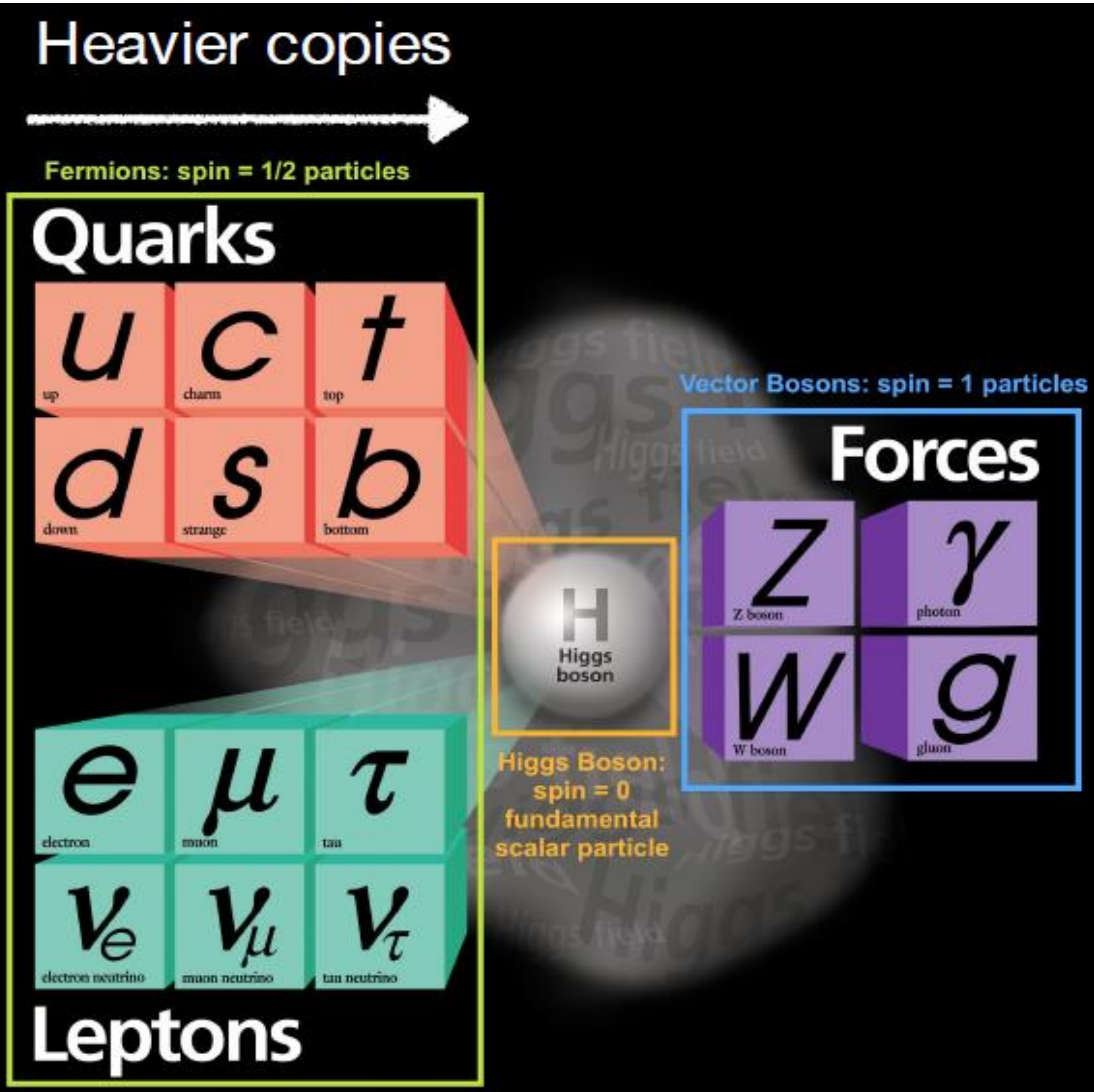
Theoretically it was desperately needed, it provided a mechanism in which the W and Z could require masses without spoiling theory.

You’ve probably heard, but the Higgs was discovered in 2012 at CERN.





The Standard Model

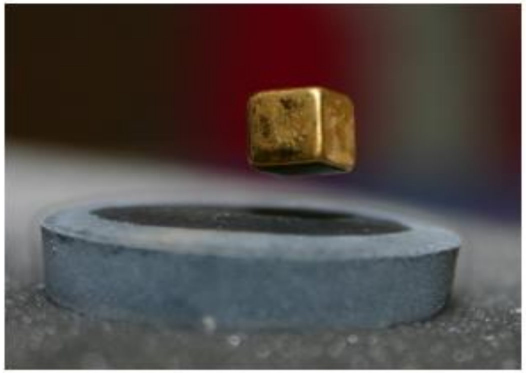


Fermions and Boson

Fundamental characteristics of particles : Spin (”self angular momentum”)

- Integer values (0, ±1, …) → **Bosons**
- Half integer values (±1/2, ±3/2, …) → **Fermions**

Bosons (Cooper pairs …) can be described by **common wavefunction** → Funny effects (super conductivity, super fluidity, …)



Fermions (electrons or protons …) must be in different states

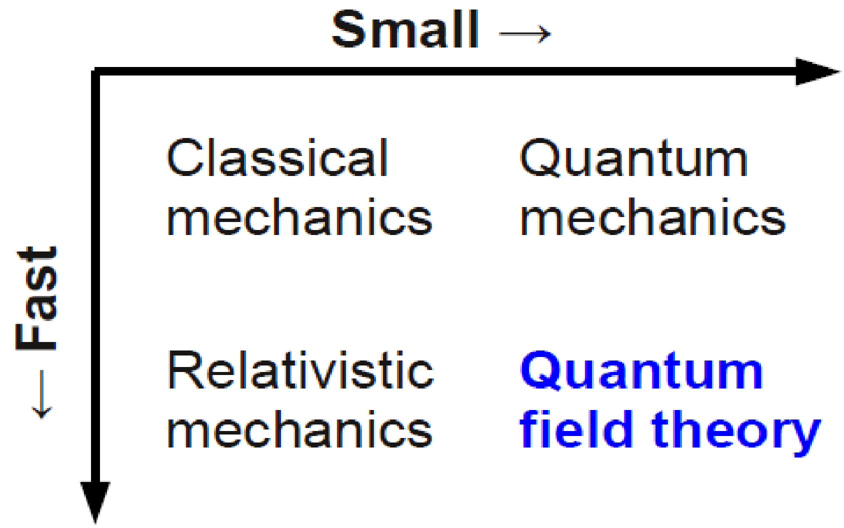
→ **Pauli's exclusion principle** (basis of all chemistry … and much more)

Satyendranath Bose

Enrico Fermi
(NP 1938)

Wolfgang Pauli
(NP 1945)

Quantum Field Theory



Small →

↓ Fast

Classical mechanics

Quantum mechanics

Relativistic mechanics

Quantum field theory

First major achievement: Dirac's equation for free electrons (and positrons)

$$E^2 - \mathbf{p}^2c^2 = m^2c^4$$

$$E = \pm\sqrt{\mathbf{p}^2c^2 + m^2c^4}$$

Interpretation of negative energies: sea of electrons → holes in sea act as positively charged electrons → confirmed by Anderson 1932

Paul Dirac
(NP 1933)

Carl Anderson
(NP 1936)

QFT – Gauge Interactions

Example:

Requirement: Lagrangian $\mathcal{L} = \frac{1}{2}(\partial_\mu \Phi)^T \partial^\mu \Phi - \frac{1}{2} m^2 \Phi^T \Phi$

invariant under special local transformations *G*(*x*) $\Phi \mapsto \Phi' = G\Phi$

Invariance is in general not guaranteed, since $\partial_\mu(G\Phi) \neq G(\partial_\mu \Phi)$

Introduce covariant derivatives (with gauge fields A_μ) $D_\mu = \partial_\mu + gA_\mu$

→ **Locally gauge invariant Lagrangian** $\mathcal{L}_{\text{loc}} = \frac{1}{2}(D_\mu \Phi)^T D^\mu \Phi - \frac{1}{2} m^2 \Phi^T \Phi$

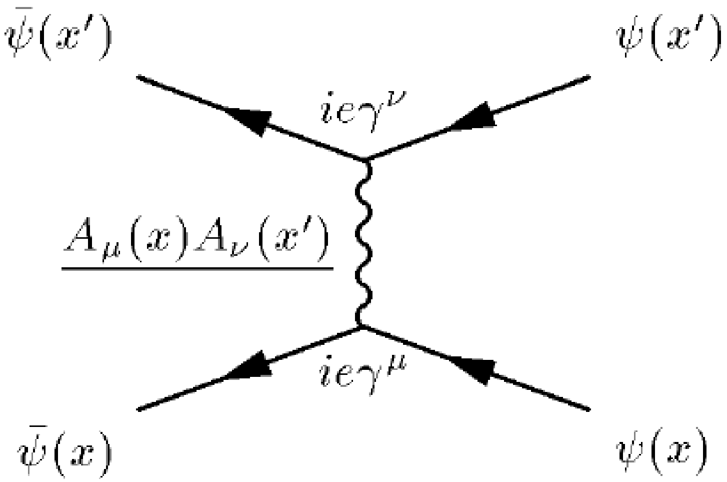
→ **Interaction terms:** $\mathcal{L}_{\text{int}} = \frac{g}{2} \Phi^T A_\mu^T \partial^\mu \Phi + \frac{g}{2}(\partial_\mu \Phi)^T A^\mu \Phi + \frac{g^2}{2}(A_\mu \Phi)^T A^\mu \Phi$

→ **Gauge fields (gauge bosons) are interaction ”particles”**

General recipe for a QFT:

- Write down Lagrangian of mass, kinetic, and interaction terms
- Quantize fields
- Decribe scattering theory with quantized fields

Feynman Diagrams/Renormalisation



Feynman diagrams:

Powerful tool to write down scattering amplitudes (also for higher order perturbations)

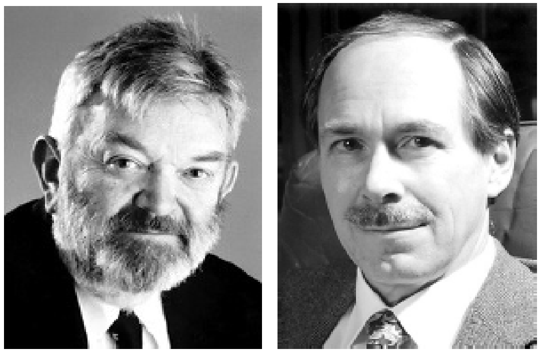
Feynman rules:

Set of rules to get from a Feynman diagram to the mathematical expression

R. Feynman
(NP 1965)

In QFTs perturbation theory is only **valid for finite energy range** → **divergences in calculation of scattering amplitudes**

Renormalization is a technique to remove these divergences



M. Veltman and G. 't Hooft
(NP 1999)

Quantum Electro Dynamics

Lagrangian invariant under local ($\theta=\theta(x)$) phase transition: symmetry group U(1)

$$\psi \mapsto e^{i\theta}\psi$$

Appropriate covariant derivative, with gauge field A_μ

$$D_\mu = \partial_\mu - i\frac{e}{\hbar}A_\mu$$

→ QED Lagrangian

$$\mathcal{L}_{\text{QED}} = \bar{\psi}(i\hbar c\,\gamma^\mu D_\mu - mc^2)\psi - \frac{1}{4\mu_0}F_{\mu\nu}F^{\mu\nu}$$

A_μ is the photon field!

Side remark: Generators of U(1) group commute (abelian group) → Gauge bosons have no charge (photons are electrically neutral)→ no self interaction

As in classical mechanics (Noether's Theorem):

Symmetry ↔ conserved quantity

Electroweak Theory

A. Salam, S. Glashow, and S. Weinberg (NP 1979)

Local symmetry:

$SU(2)_L \otimes U(1)$

Charges:

- Weak isospin I_3
- Weak hypercharge $Y = 2Q - 2I_3$

Gauge fields: W, B mix to $W^{\pm}$, Z^0, and γ

Generators of $SU(2)_L$ do not commute (non-abelian group)

→ Self interaction

By construction all gauge bosons are massless (to keep local invariance)

However, short range of interaction implies heavy particles

Electroweak Gauge Bosons

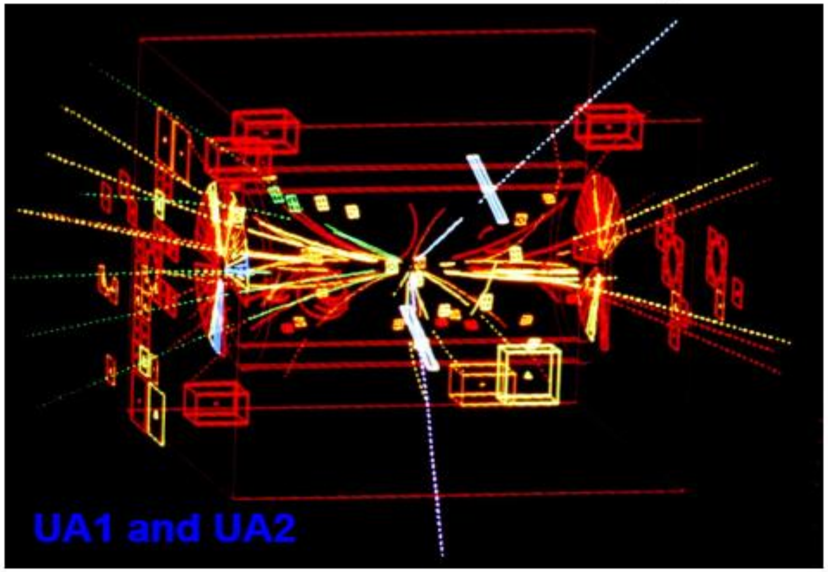
- Observation of neutral current in 1973
- Observation of *W* in May 1983 (and a few month later also the *Z*) at UA1 and UA2

$$M_W \sim 80.4 \text{ GeV}$$

$$M_Z \sim 91.2 \text{ GeV}$$

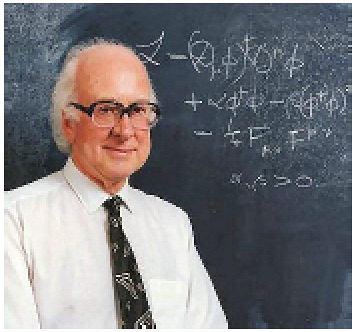
→ **Heavy particles!**

C. Rubbia and S. van der Meer (NP 1984)



The Higgs mechanism

Formalism to obtain massive gauge bosons while keeping invariance of *L* intact by spontaneous symmetry breaking



Peter Higgs

Independently derived by Englert, Brout, Kibble, Hagen, Guralnik

Lagrangian of complex scalar Higgs field ϕ

$$\mathcal{L}_{\text{Higgs}}(\phi,\ A) = (\hat{D}_\mu \phi)^\dagger (\hat{D}^\mu \phi) + \mu^2 \phi^\dagger \phi - \lambda(\phi^\dagger \phi)^2$$

If $\mu^2 > 0$ → trivial minimum at $\phi=0$
If $\mu^2 < 0$ → non trivial, degenerated minimum

Vaccum expectation value $|\langle 0|\phi|0\rangle| = v = \sqrt{\frac{-\mu^2}{2\lambda}}$

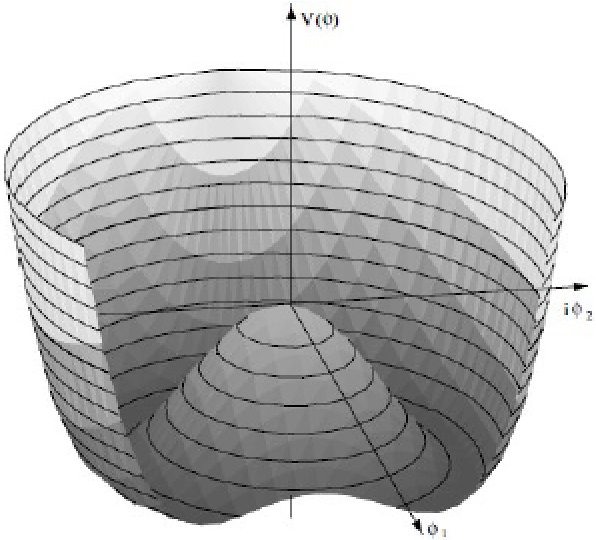
A. Choose arbitrary ground state in minimum

B. Expand Higgs field

C. Covariant derivatives → massive gauge bosons

$$M^2_{W^\pm} = \frac{g^2 v^2}{4} \qquad M^2_{Z^0} = \frac{(g^2 + g'^2)v^2}{4}$$

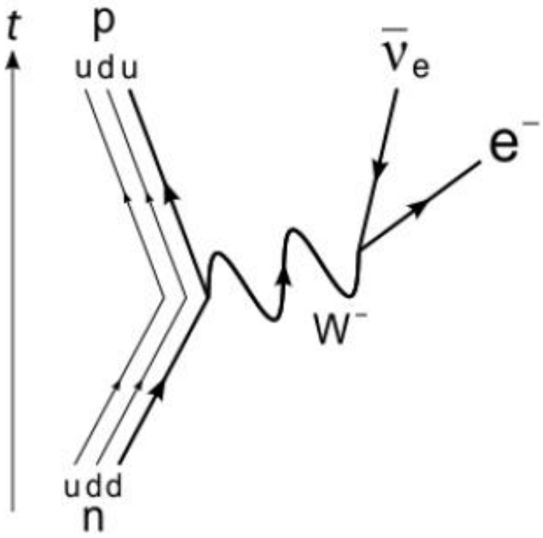
With *g* and *g'* as coupling constants of $SU(2)_L$ and U(1)

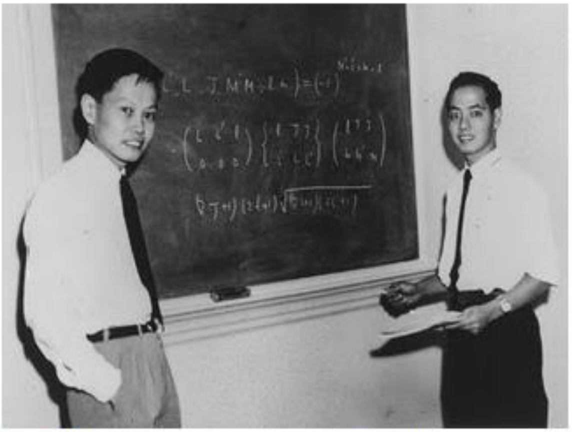


Mexican hat potential

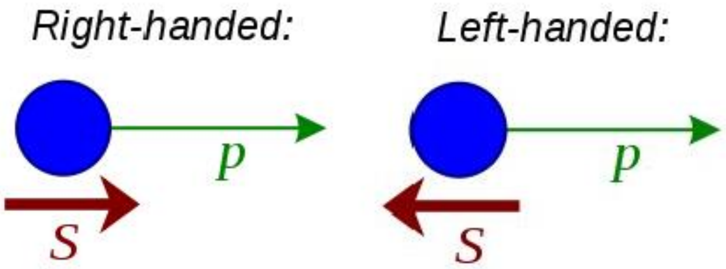
EW Decay – C and P violation

- Classical gravitation, electromagnetism, and the strong interaction are invariant under charge *C* and parity *P* ("Mirror symmetry") transformations
- Yang and Lee: *P* could be violated in EW interactions
- **Observation by Wu:** cryogenic Co^{60} in strong magnetic field → strong asymetry of direction of emitted electrons → maximal *P* violation
- *C* and *P* both violated by EW interactions, but *CP* (mostly) concerved




C. N. Yang and T.-D. Lee (NP 1956)


C. S. Wu

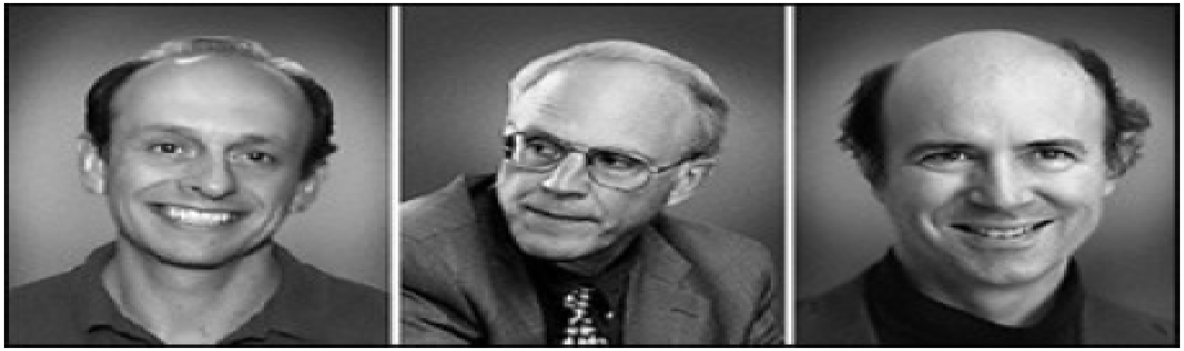


Quantum Chromodynamisc

- All ordinary matter consists of fermions and the largest fraction is carried by nucleons made of quarks and gluons
- **Strong interaction:** SU(3) ⟶ 8 massless gluons as gauge bosons
  - Quarks (and gluons) carry "color" charge
  - Gluon self interaction

  ⟶ Coupling constant decreasing with energy: "assymptotic freedom" at high energies

  ⟶ Quarks and gluons don't exist as free particles but as color neutral bound states: Mesons (quark-antiquark) or Baryons (three quarks)



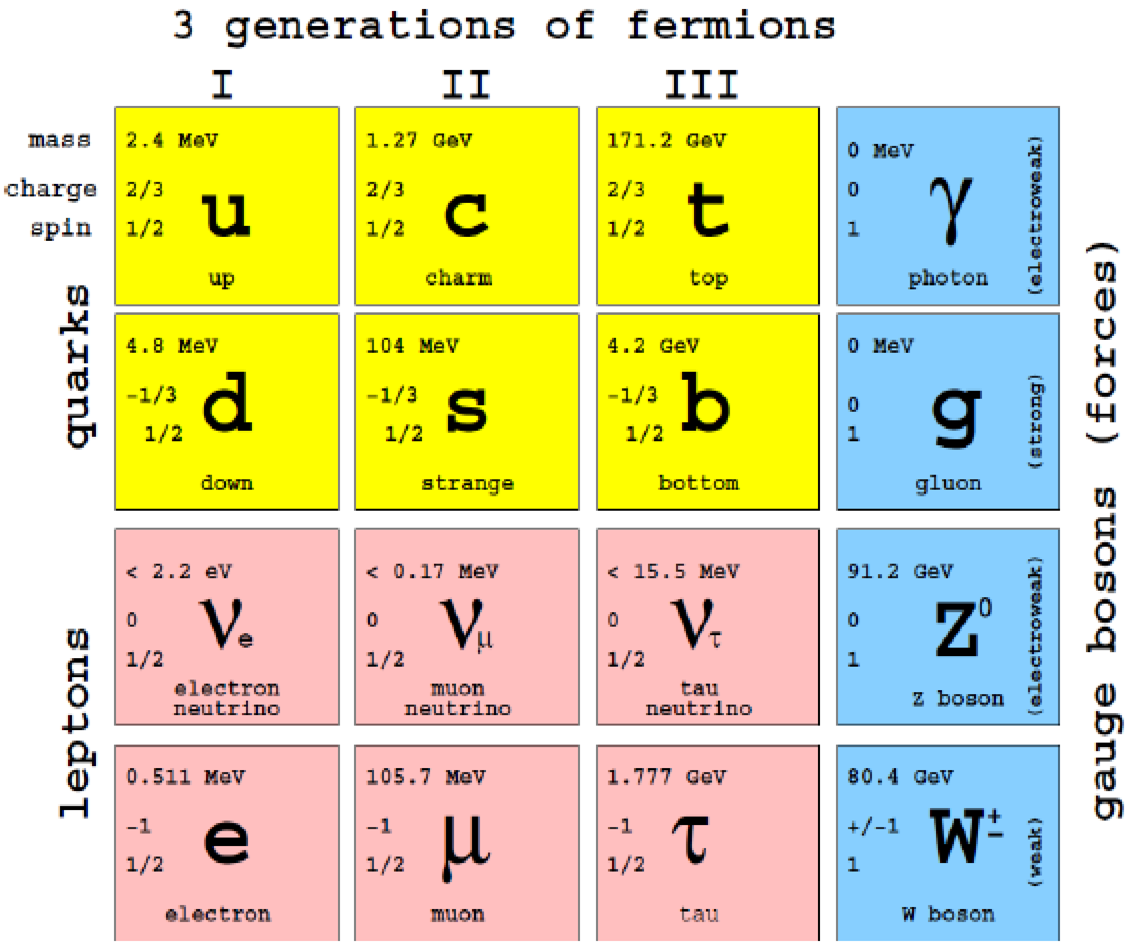
D. Politzer,
D. Gross,
F. Wilczek
(NP 2004)

The Standard Model

- Interactions described by gauge groups:

  $$U(1)\otimes SU(2)_L \otimes SU(3)_C$$

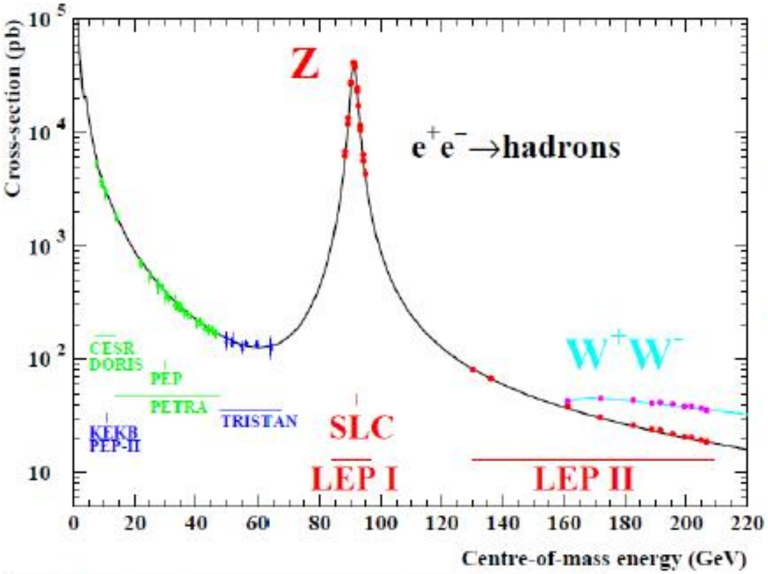
- Higgs boson last missing particle
- **All measurements from colliders in excellent agreement with the SM**



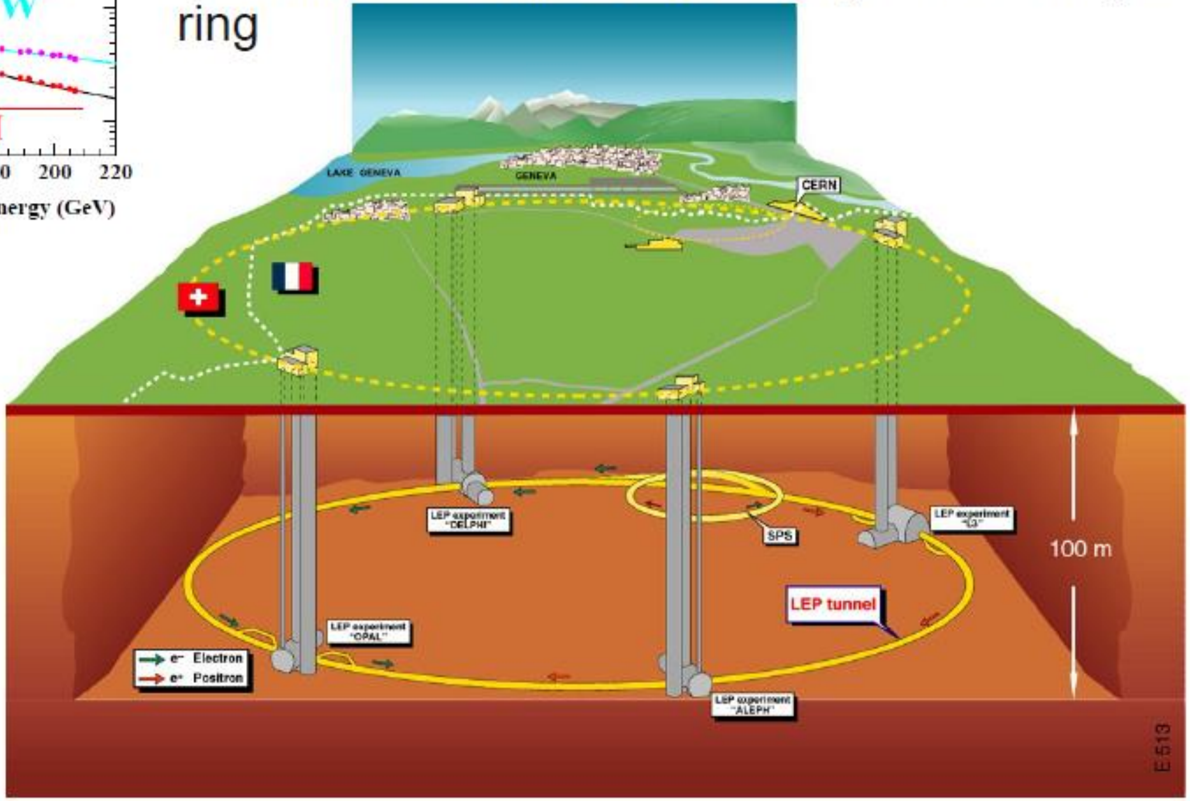
3 generations of fermions

mass charge spin	I	II	III	gauge bosons (forces)
quarks	2.4 MeV 2/3 1/2 **u** up	1.27 GeV 2/3 1/2 **c** charm	171.2 GeV 2/3 1/2 **t** top	0 MeV 0 1 γ photon (electroweak)
	4.8 MeV -1/3 1/2 **d** down	104 MeV -1/3 1/2 **s** strange	4.2 GeV -1/3 1/2 **b** bottom	0 MeV 0 1 **g** gluon (strong)
leptons	< 2.2 eV 0 1/2 ν_e electron neutrino	< 0.17 MeV 0 1/2 ν_μ muon neutrino	< 15.5 MeV 0 1/2 ν_τ tau neutrino	91.2 GeV 0 1 Z^0 Z boson (electroweak)
	0.511 MeV -1 1/2 **e** electron	105.7 MeV -1 1/2 μ muon	1.777 GeV -1 1/2 τ tau	80.4 GeV +/-1 1 $W^\pm$ W boson (weak)

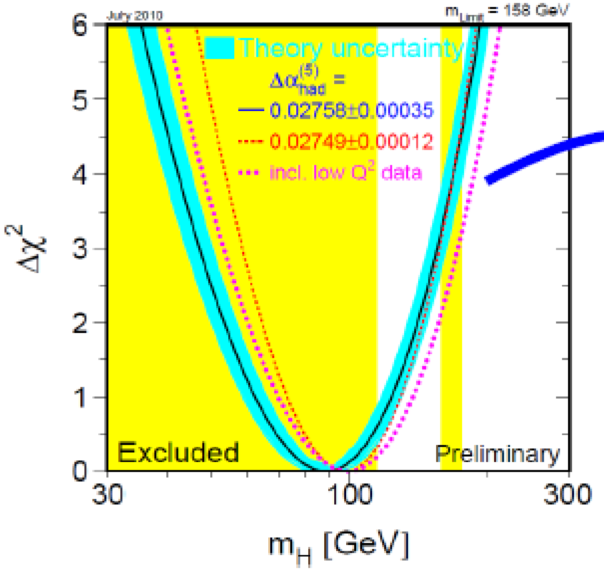
Large Electron Positron Collider



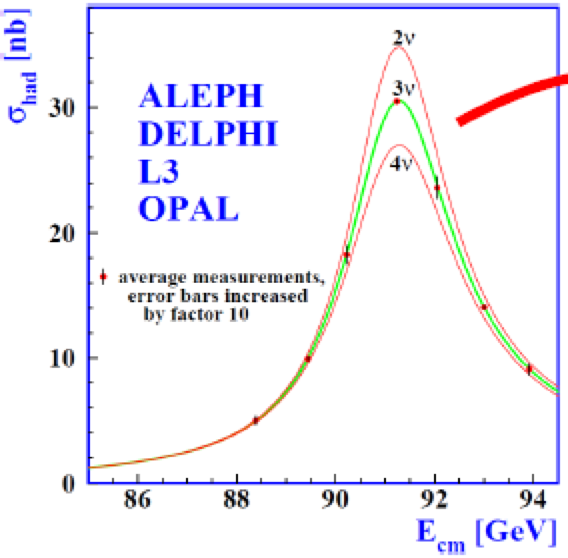
- 1989 … 2000: electron-positron collisions with $\sqrt{s}$ up to 209 GeV
- Very clean events → high precision measurements possible
- Former LEP tunnel now hosting LHC storage ring



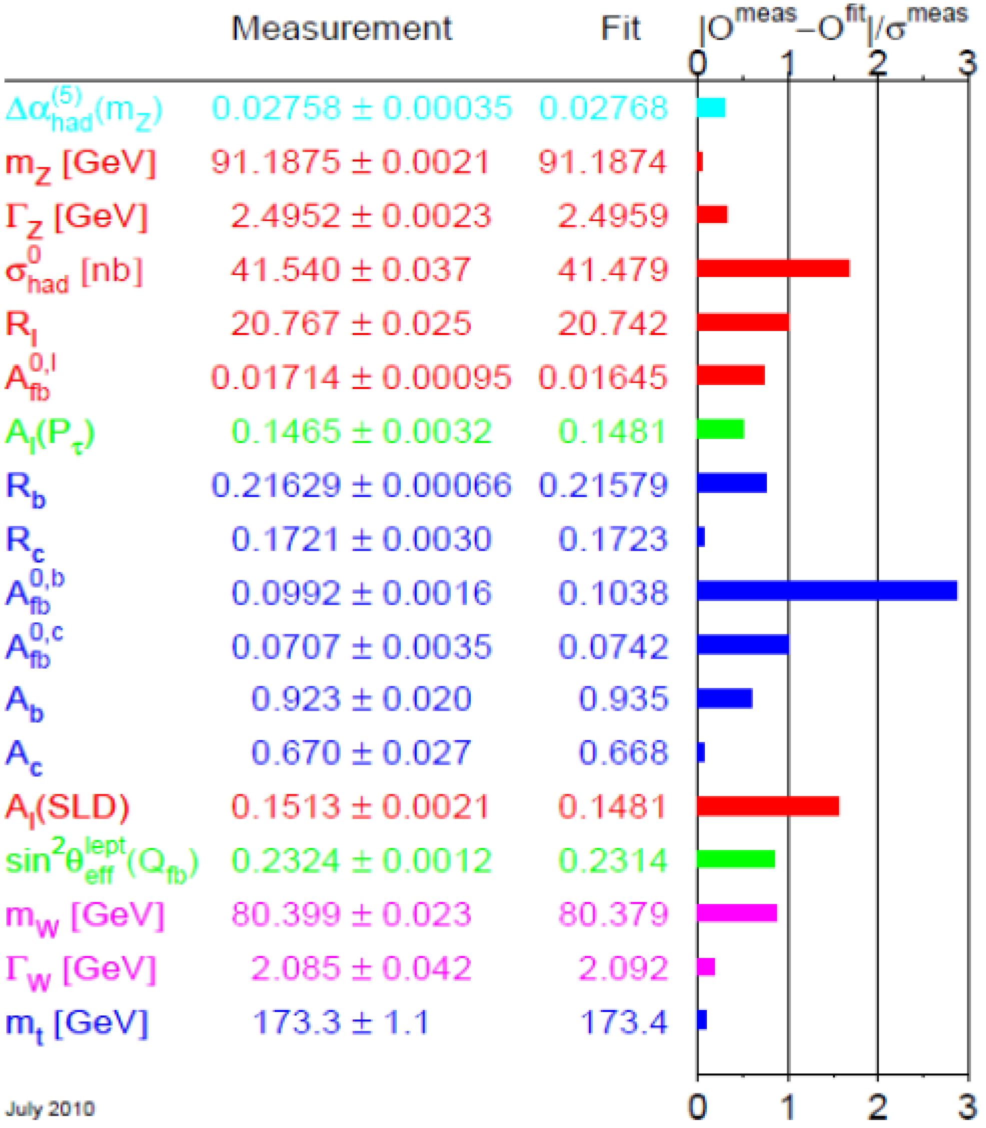
Electroweak precision data



Indirect Higgs limit



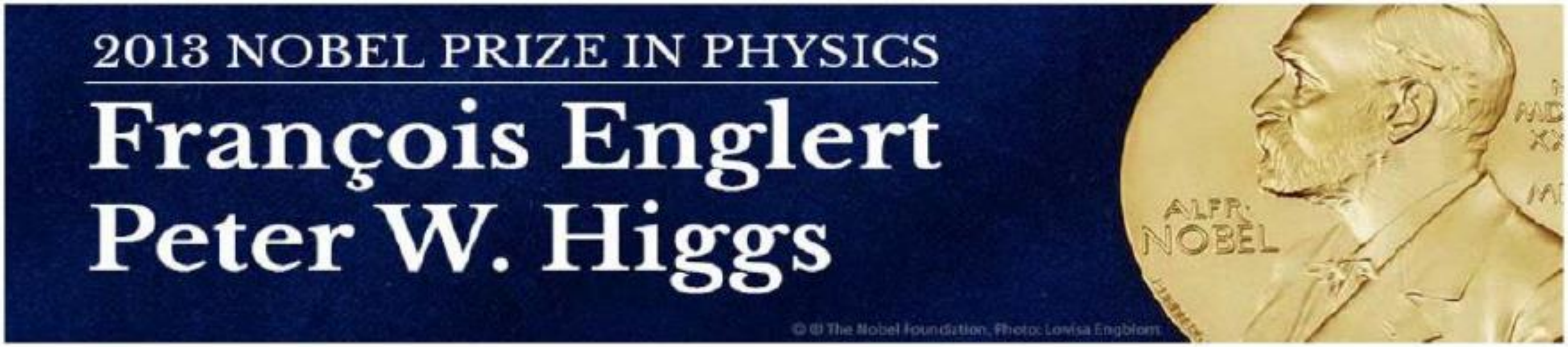
Three light neutrino families!



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ^0_{had} [nb]	41.540 ± 0.037	41.479
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.399 ± 0.023	80.379
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.3 ± 1.1	173.4

July 2010

4-th of July 2012, ATLAS and CMS experiments at Large Hadron Collider at CERN announced observation of a new particle, consistent with predicted by so called „Higgs mechanism”.



2013 NOBEL PRIZE IN PHYSICS

François Englert
Peter W. Higgs

© The Nobel Foundation, Photo: Lovisa Engblom

THE BEH-MECHANISM, INTERACTIONS WITH SHORT RANGE FORCES AND SCALAR PARTICLES

8 October 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert and Peter Higgs

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

The neutrino

- Continous spectrum of electrons from β-decay

  → new undetectable particle predicted by Pauli in 1930
- First observation by Poltergeist experiment in inverse β-decays in 1957

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

- Observation of the myon neutrino in 1962

F. Reimes
(NP 1995)

L. Ledermann, M. Schwartz, J. Steinberger
(NP 1988)

And much more spectacular physics:

- Solar neutrino problem …
- Neutrino oscillations …
- Neutrino masses …
- Cosmological neutrinos …
- Neutrinos from super novae …

The neutrino oscilation

Nobel Prize in physics in 2015

Takaaki Kajita and Artur B. McDonald

for discovery of the neutrino oscillations, which shows that neutrino has mass.

Nobel Prizes in Elementary Particle Physics


Sin-Itiro Tomonaga


Julian Schwinger


Richard P. Feynman


Sheldon Lee Glashow


Abdus Salam


Steven Weinberg


Leon M. Lederman


Melvin Schwartz


Jack Steinberger


Carlo Rubbia


Simon van der Meer


Georges Charpak


Gerardus 't Hooft


Martinus J.G. Veltman


M. Gell-Mann

GREEN - theoretical
BLUE - experimental

1964: „Higgs mechanism” was born

1957 – C. N. Yang, T. Lee
1965 – S. I. Tomonaga, J. Schwinger, R.P Feynman
1969 – M. Gell-Mann
1976 – B. Richter and S. Ting
1979 – S.L. Glashow, A. Salam, S. Weinberg
1980 – J. Cronin, V. Fitch
1984 – C. Rubbia, S. van der Meer
1988 – L. M. Lederman, M. Schwartz, J. Steinberger
1990 – J. Friedman, J. Kendall, R. Taylor
1992 - G. Charpak
1995 – M. Perl, F. Reines
1999 - G. tHooft, M. J. Veltman
2004 - D. J. Gross, H. D. Politzer, F. Wilczek
2008 – Y. Nambu, M. Kobayashi, T. Masakawa
2013 – F. Englert and P. Higgs
2015 - T. Kajita and A. B. McDo

2012: „Higgs particle” was discovered

And then what?

Is the end of the story? For the SM yes, but for fundamental physics, No!

We know that SM is not the complete theory of nature, some of tis problem are:

- **No dark matter**
- **Not enough CP violation to account for Matter/Anti-Matter asymmetry in the Universe.**
- **No explanation of the particle specrum, why is the Higgs so light?**
- **Neutrinos?**
- **. . .**