THE STANDARD MODEL OF PARTICLE PHYSICS

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WHAT MAKES UP THE UNIVERSE ?

- This question has long puzzled humanity, since the rise of our species.
- It would be amazing to go back in time and be in the shoes of our ancestors, and guess what they thought about the constituents of our universe and our size in it !
- The Greeks where fist to propose an ‘atomic theory’.
- John Dalton, brought the Greek atomic theory to life, by stating more scientific and testable proposal.

PRELIMINARIES : GROUP THEORY

- In physics, symmetry is very important. It can simplify enormous calculations and help theriticians to classify things according to the symmetries they share.
- A group is a Set with “multiplication” that satisfies the following properties:
  1. Closure
  2. Existence of identity
  3. Existence of inverse
- A very simple example of a group is the set of the nth order complex roots of 1

PRELIMINARIES: QUANTUM FIELD THEORY

- A field is a function which depends of spacetime coordinates. It could be scalar function, vector or Tensor-valued function of any rank.
- Spinors are a special case of tensors, they are more complex, and they are characterized by the way they respond to rotation of coordinates. In physics, spinor fields describe fields of half-integer spin particles
- Spin is a crucial in QFT for classifying particles, integer spin particles are associated to Bose-Einstine statistics (Bosons) and half-integer spin particles are associated to Fermi-Dirac statistics (Fermions).

In Classical Fields, the interaction between “particles "is done via forces. While in QFT, interaction is held by force carrying virtual particles, the number of these particles exchanged is proportional to the product of charges in the interaction.

PRELIMINARIES: GAUGE THEORY

- Consider a magnetic flux field, given by :

$$\underline{\boldsymbol{B}} = \nabla \times \underline{\boldsymbol{A}}$$

Any *continuous* transformation of the vector potential given by

$$\boldsymbol{A} \rightarrow \boldsymbol{A} - \nabla\Lambda$$

1) Forms a group 2) Leaves **B** unchanged

We can say that the magnetic flux field is *gauge invariant.* And the transformation above is called *Gauge transformation.*

In a VERY short and simplified sense we define a gauge field theory being the theory of fields which their Lagrangian is invariant under continuous (Lie) group of local transformation

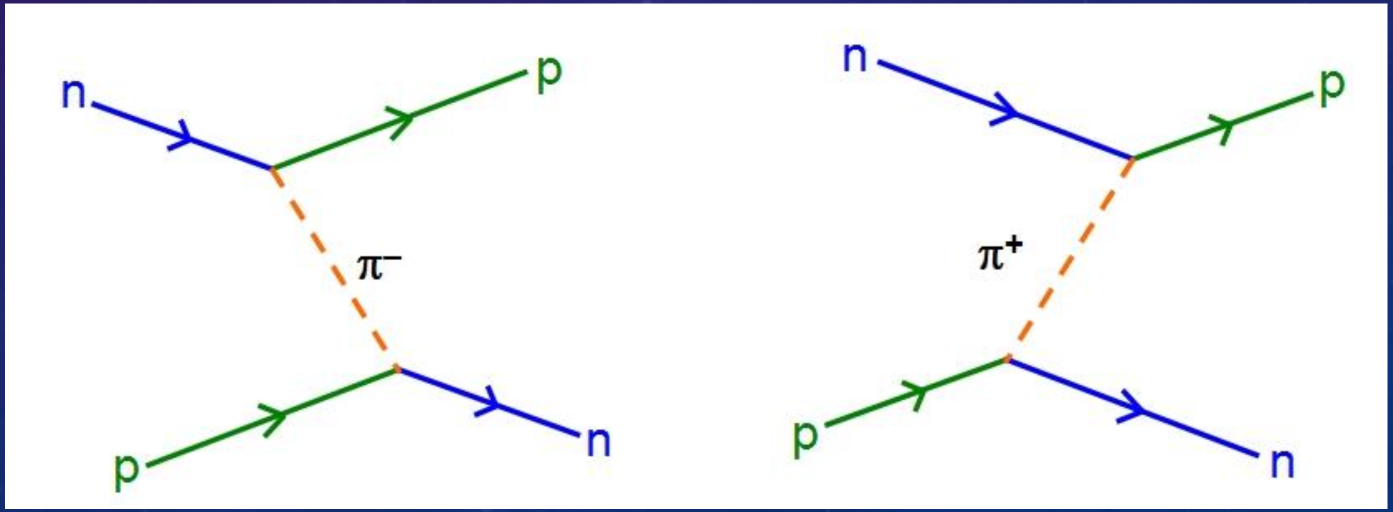
The definition may seem rather abstract, but gauge theory is the foundation of the Standard Model.

PARTICLE PHYSICS OF THE 30'S- YUKAWA'S THEORY

- In the late 1930's H. Yukawa postulated a theory to explain the strong nuclear interaction via "meason exchange
  $\mathcal{L}_{meason} = \frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi - \frac{1}{2}\mu^2\phi^2 - \lambda\phi^4$ (renormalizable) lagrangian of massive (self-interacting mason)

  Moreover, the action of a psedoscalar meson field (ϕ) with Dirac baryon field is given by

$$S = \int d^4x[\frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi - \frac{1}{2}\mu^2\phi^2 - \lambda\phi^4 + \psi^{\dagger}(i\not{D} - m)\psi - g\psi^{\dagger}\phi\psi]$$



MORE ON YUKAWA'S THEORY*

- Consider the energy of relativistic particle

$$E^2 = m^2c^4 + p^2c^2$$

using the operator relations:

$$\hat{E} \equiv \frac{i\hbar\partial}{\partial t}, \hat{p} = -i\hbar\nabla$$

We have the Klein –Gordon Equation :

$$\nabla^2\psi = -\frac{m^2c^2}{\hbar^2}\psi - \frac{1}{c^2}\frac{\partial^2\psi}{\partial t^2}$$

In spherical coordinates (dropping the time dependence term and using spherical symmetry)

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r^2\frac{\partial U}{r}\right) = \frac{m^2c^2}{\hbar^2}$$

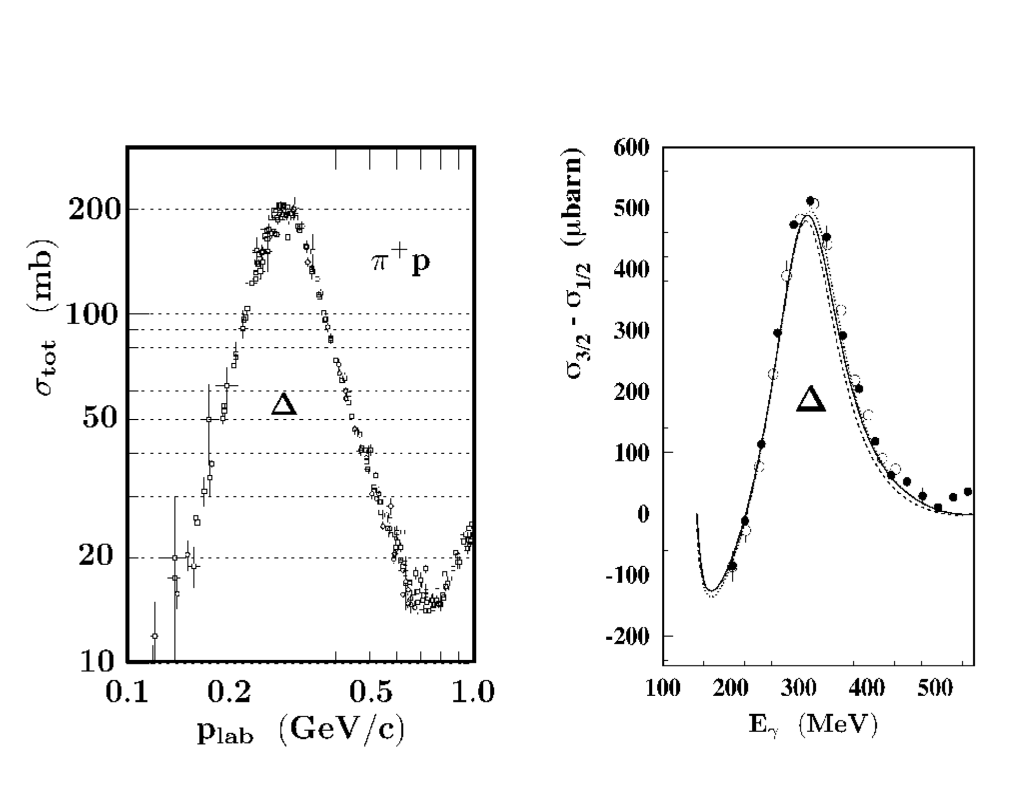
Has an integral of (Yukawa potential)

$$U(r) = \frac{g}{4\pi r}e^{-\frac{r}{R}}$$

$$R = \frac{\hbar}{mc}$$

PARTICLE PHYSICS IN THE 60'S… LOTS AND LOTS OF PARTICLES!

- With the development of particle accelerators, new particles were discovered almost every week!
- There is a huge list of particles can be found, for example (p,n) (Δ+, Δ-, Δ°, Δ*) (π±, π°) (ɳ) (ρ)…… etc
- Some, like the Δ family are called **resonances**, strongly interacting particles are called *Hadrons*All these particles are thought to be elementary.



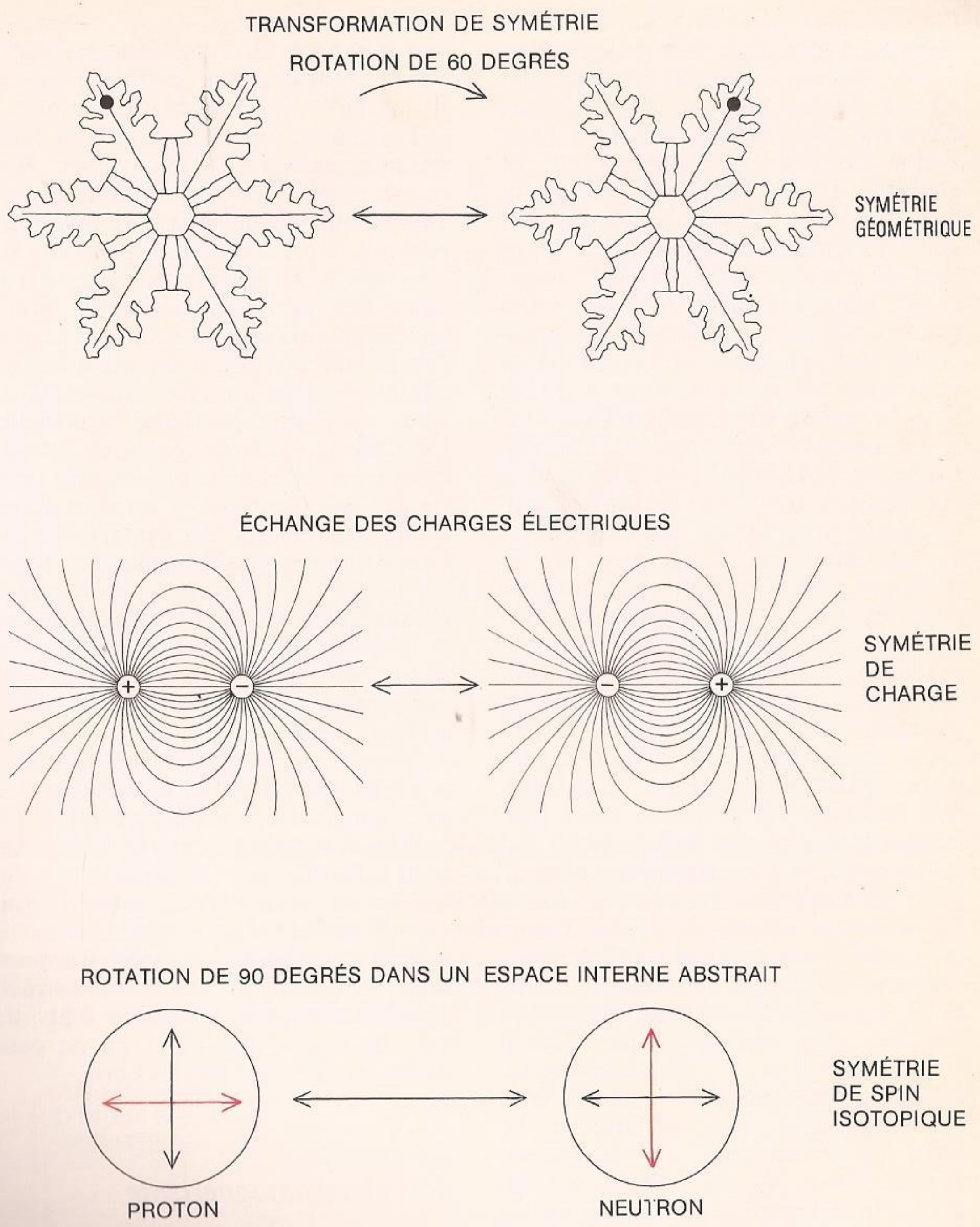
π°- proton scattering cross-section showing resonance at the mass of the Δ+

WHO ORDERED THOSE ?

- A discovery of more massive and more stable set of particles, who decayed via weak interaction (called strange particles) confused physicists. They seemed to have a new quantum number (Strangeness) that was conserved via strong interaction.
- The μ was discovered as well, it seemed like an exact replica of the electron, but more massive. Leptons (the light ones) are no longer “light”.
- It was becoming clear that there is a new *generation* of matter

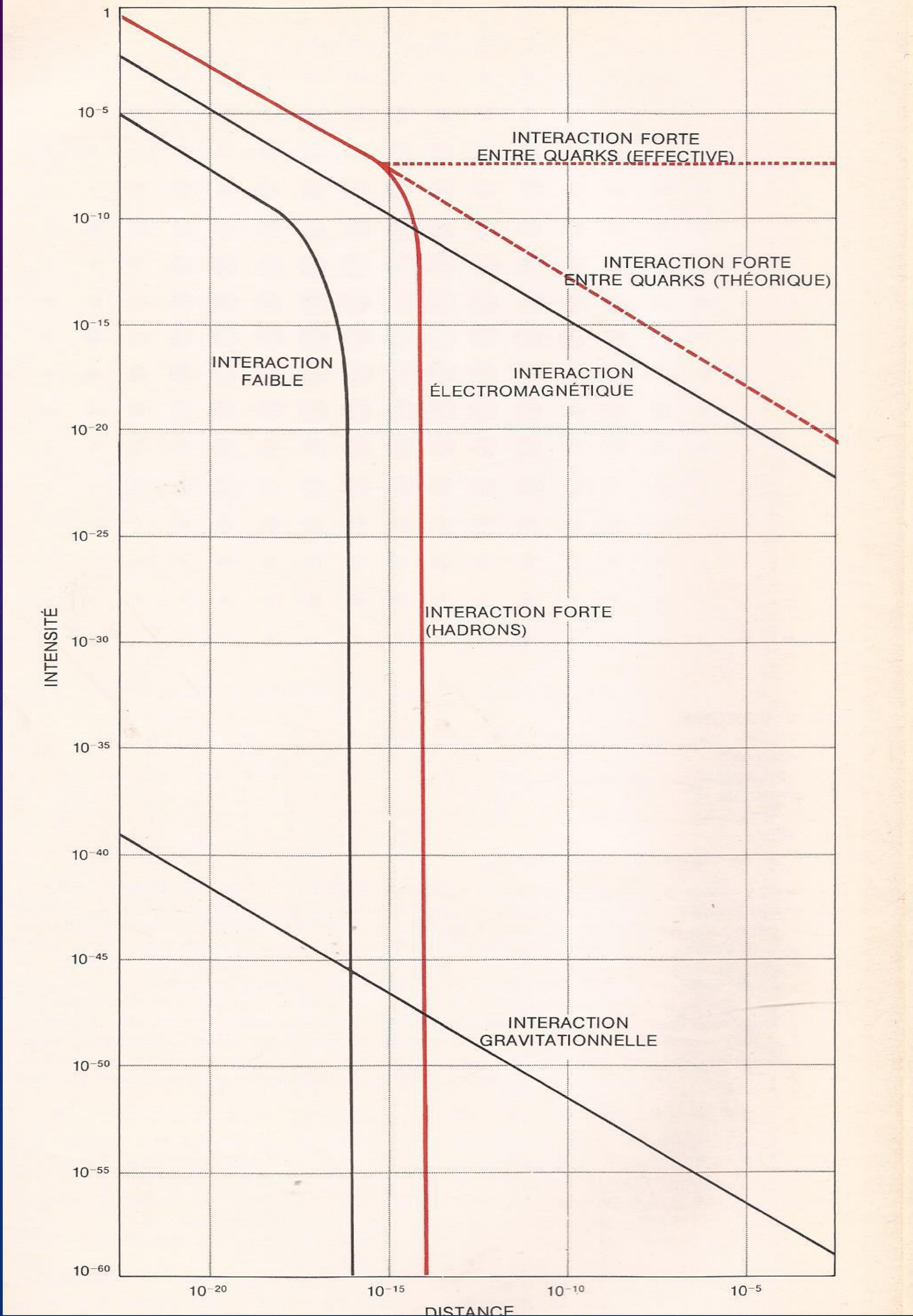
SU(2) AND ISOSPIN SYMMETRY

- SU(2) is a group of transformation *homomorphic* to the group of “Real”3x3 rotations SO(3).
- The symmetry of isospin can be pictured like a symmetry of geometrical object under rotation.
- To a very good approximation, Hadrons of the same family (like proton and neutron) have this symmetry and interact strongly in the same way, as if the strong interaction is blind to the fact that the hadron is either proton or neutron.



FUNDAMENTAL INTERACTIONS

- Theoretical developments of QFT and Gauge theory, along with the experimental observation came to conclude that there are four Fundamental interactions:
- Strong Interaction: primary and residual. Described by QCD and Yukawa's theory (as seen before).
- Electromagnetic interaction described by QED
- Weak interaction (Quantum flavour dynamics and electroweak model)
- Gravitation (beyond Standard model).



QUANTUM ELECTRODYNAMICS AND U(1)

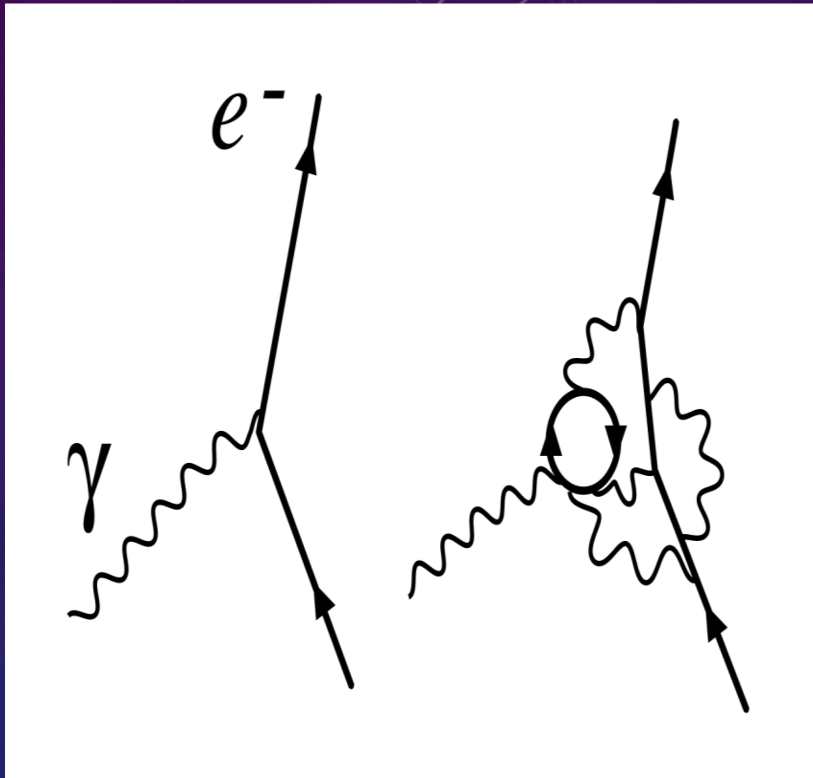
- The most accurate theory ever postulated, QED is matching observations by an error factor of ten parts in a billion
- It describes the interaction between charged particles (and ones with dipole moment)
- Quantization of the Classical electromagnetic theory.

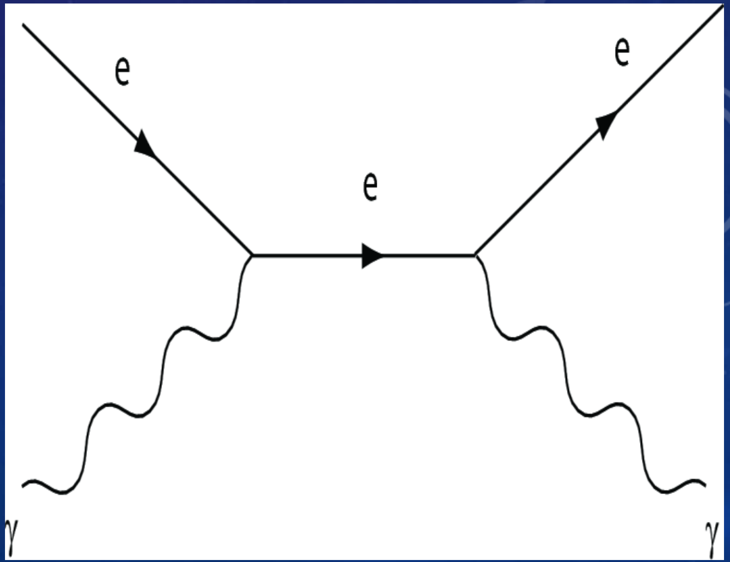
$$\mathcal{L}_{QED} = \psi^{\dagger}\ (i(\gamma^{\mu}\mathcal{D}_{\mu} - m)\psi \quad - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

where,

$F_{\mu\nu} = \partial_{\mu}A_{\nu} - \partial_{\nu}A_{\mu}$ Faraday Tensor

- QED is an abelian gauge theory with symmetry group U(1) [Circle group] which has one generator , t there is one gauge boson (due to the local symmetry)
- One can think poetically about QED, it is the interaction that allows us the Love, see and hear art and smell perfumes and flowers… or even think !





MORE ON QED AND GAUGE THEORY *

- We use localization of global transformation lie group (U1) on the Lagrangian of Dirac field to construct the covariant derivative, then use gauge principle to find the minimal coupling (coupling of fields by charge only). Gauge principle states that adding coupling terms between fields must preserve the gauge invariance of the largrangian
- We start by the action of Dirac field (the one that produces Dirac equation) :

$$\mathcal{S} = \int d^4x \, \langle \psi | i\hbar c \, \gamma^\mu \partial_\mu - mc^2 \, | \psi \, \rangle$$

- Consider the transformation of U(1) - localized –

$$|\psi\rangle \rightarrow e^{i\Lambda(x)} |\psi\rangle$$

  with the covariant derivative:

$$\mathcal{D}_\mu = (\partial_\mu + ieA_\mu)$$

- Applying gauge transformation of the vector potential :

$$A_\mu \to A_\mu - \frac{1}{e}\partial_\mu \Lambda$$

- The interaction lagrangian becomes:

$$\mathcal{L}_{int} = J^\mu A_\mu = \frac{e}{\hbar}\langle\psi|\gamma^\mu|\psi\rangle A_\mu \Rightarrow \mathcal{L}_{int} = \left\langle\psi\middle|i\hbar c\gamma^\mu \mathcal{D}_\mu - mc\middle|\psi\right\rangle$$

Using gauge principle and the result from classical electrodynamics we can now write the lagrangian of QED

$$\mathcal{L}_{classical} = -\frac{1}{4\mu_0}F^{\mu\nu}F_{\mu\nu} - J^\mu A_\mu$$

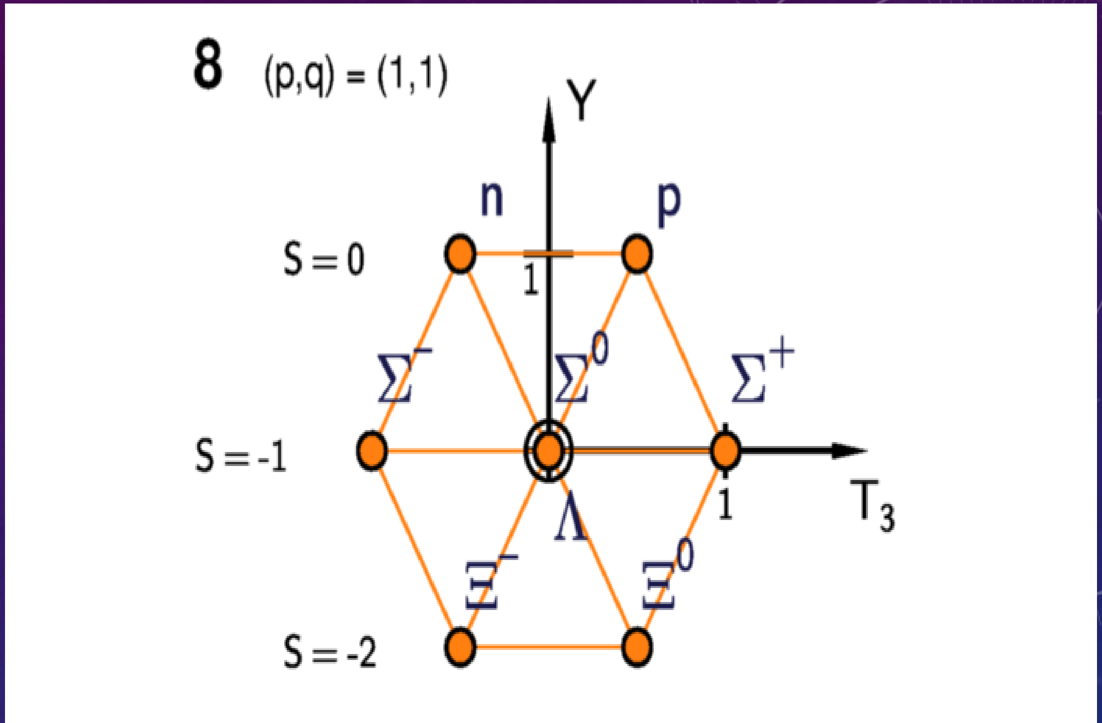
$$\mathcal{L}_{QED} = \left\langle\psi\middle|i\hbar c\gamma^\mu \mathcal{D}_\mu - mc\middle|\psi\right\rangle - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

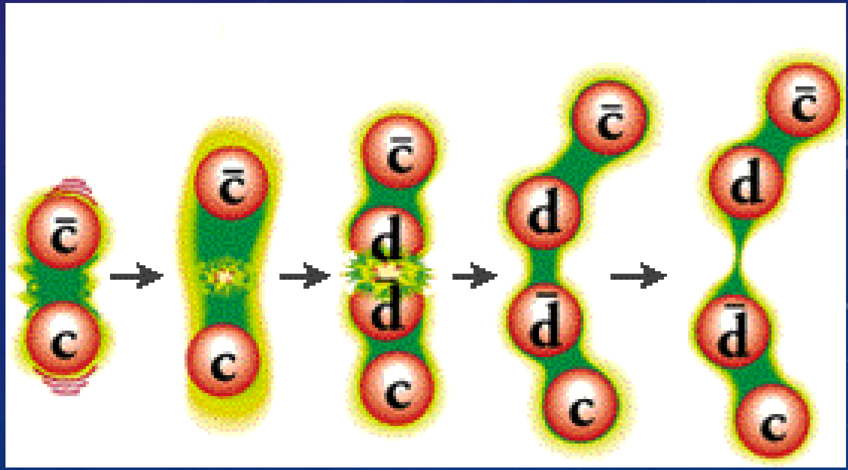
YANG-MILLS THEORY

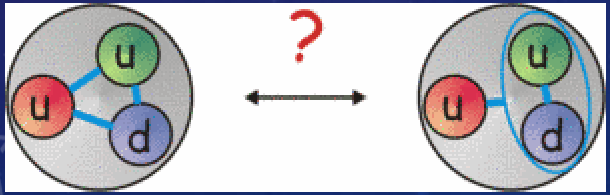
- Since U(1) symmetry group is abelian (commutative) The previous discussion was sufficient to construct QED. However, QCD and electroweak interaction are associated with non-abelian symmetry group. There is a special case of Gauge theory for any compact, semi-simple Lie group such as SU(3) and U1 x SU2 groups.
- Yang Mills theory is very important in describing the behaviour of elementary particles

SU(3) AND THE QUARK MODEL

- Hadrons seemed to form “patterns” and symmetries indicating a substructure. SU(3) is a group of transformation that was just perfect to be the model of that substructure.
- In the early 70’s The quark model was confirmed experimentally, showing that hadrons are bound-states of quarks that interacted strongly via (gauge bosons exchange)
- Quarks are confined to hadrons (and masons). One cannot isolated a single quark, as the energy flux between two quarks is formed as one tries to pull them apart causing quark-anti quark production.
- Later on, some models had shown that even further substructure can be found inside hadrons (diquark model). Such model is debatable despite there were a good supporting experimental evidence. Such model imposes a new symmetry via SU(6) group (D. B. Lichtenberg *et al,* 1968)



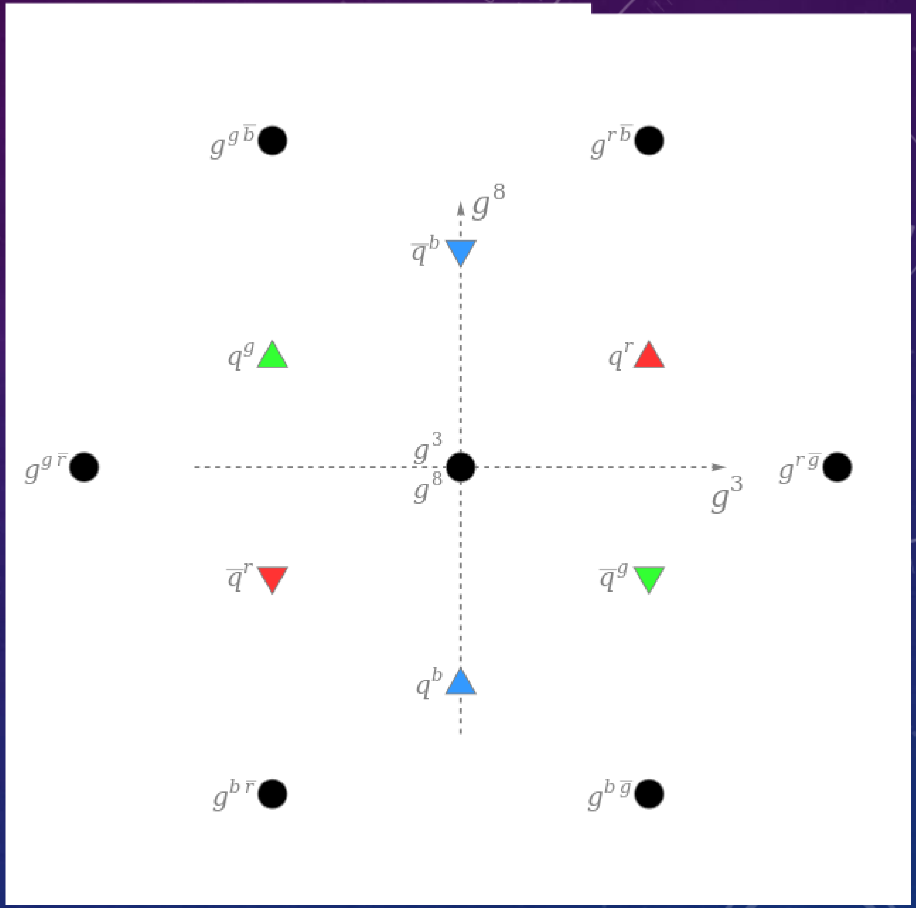




QUANTUM CHROMODYNAMICS

- QCD is a gauge theory of the SU(3) gauge group obtained by taking the colour charge to define a local symmetry. (a symmetry that acts independently at each point in spacetime) That requires an introduction of its own gauge bosons (what so called gluons).
- As SU(3) have 8 generators, from gauge theory, we have 8 gluons and their fields (like having eight types of photons in the EM interaction!)
- QCD is described by the Lagrangian:

$$\mathcal{L}_{QCD} = \psi_i^\dagger (i(\gamma^\mu \mathcal{D}_\mu - m\delta_{ij})\psi_j - \frac{1}{4} G^\alpha_{\mu\nu} G_\alpha^{\mu\nu}$$

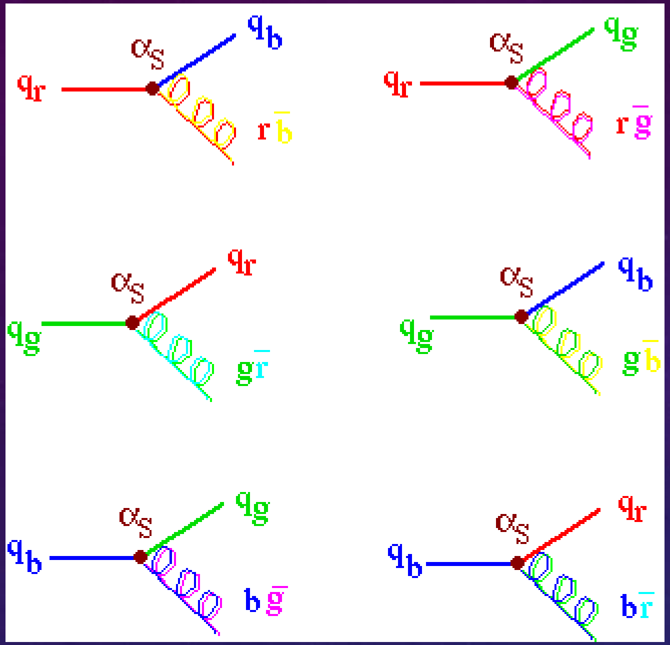


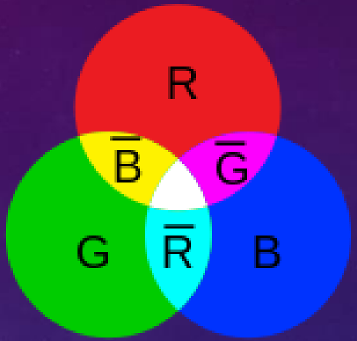
In the adjoint representation of SU(3), The Gluon field strength tensor is given by (in terms of gluon fields)

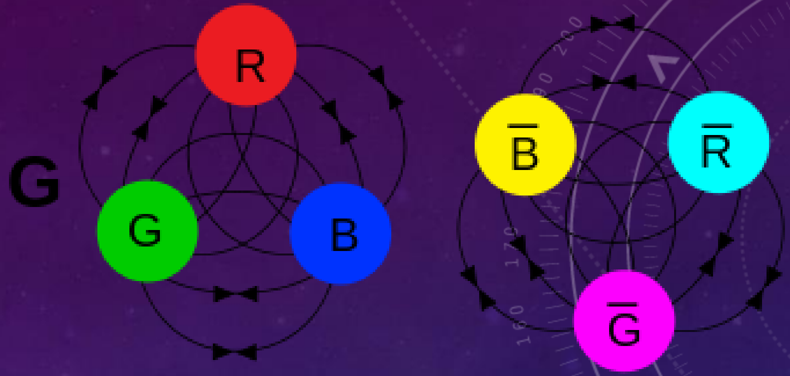
$$G^\alpha_{\mu\nu} = \partial_\mu A^\alpha_\nu - \partial_\nu A^\alpha_\mu + \boldsymbol{g f^{abc} A^b_\mu A^c_\nu}$$

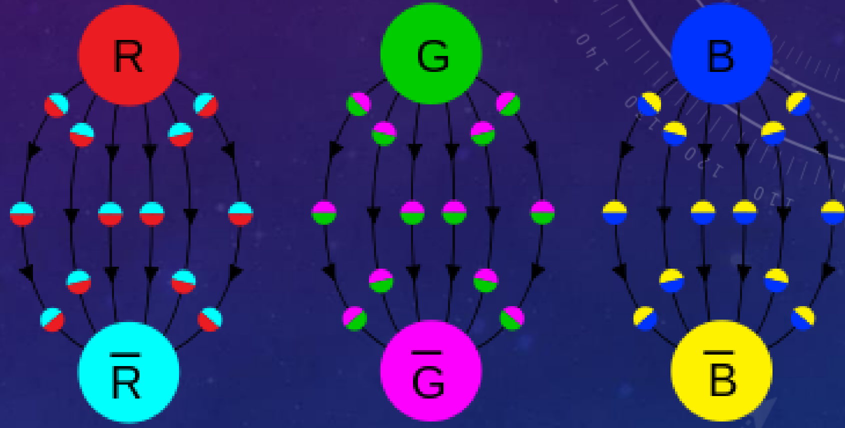
This term comes from Yang-Mills theory !

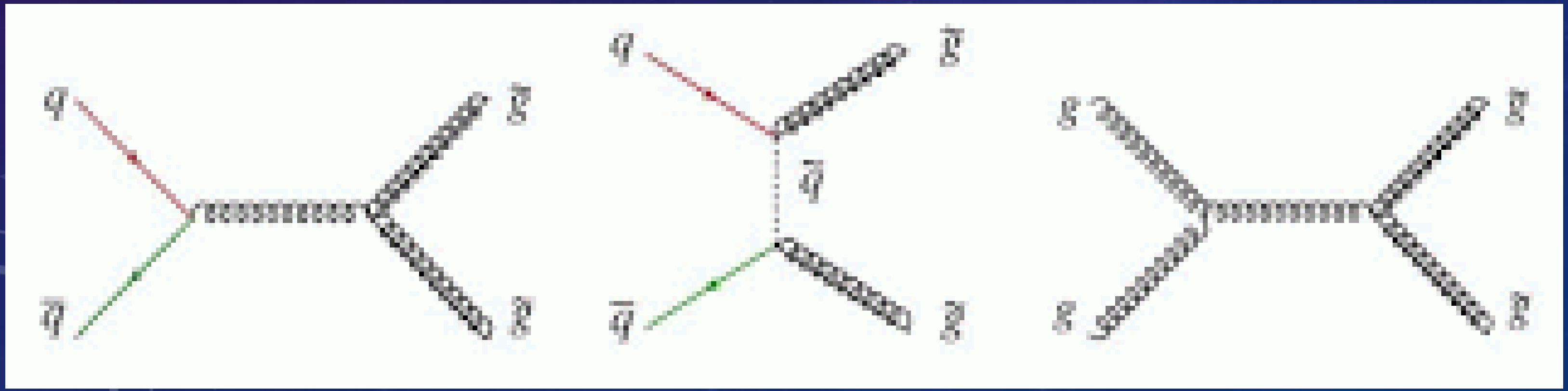
QUANTUM CHROMODYNAMICS

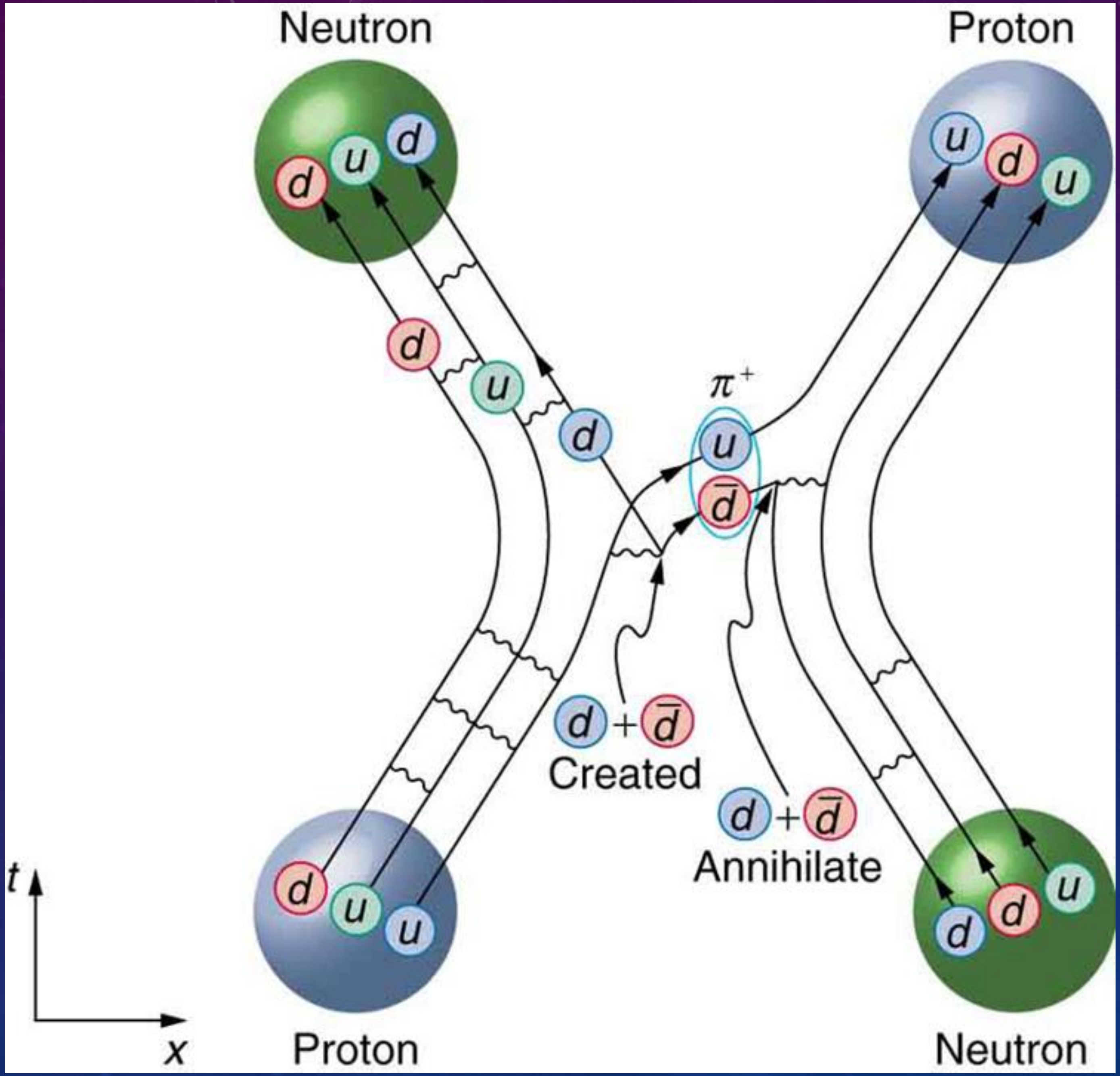












Neutron
Proton
d
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d
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d
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π^+
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$\bar{d}$
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Created
d + $\bar{d}$
Annihilate
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x
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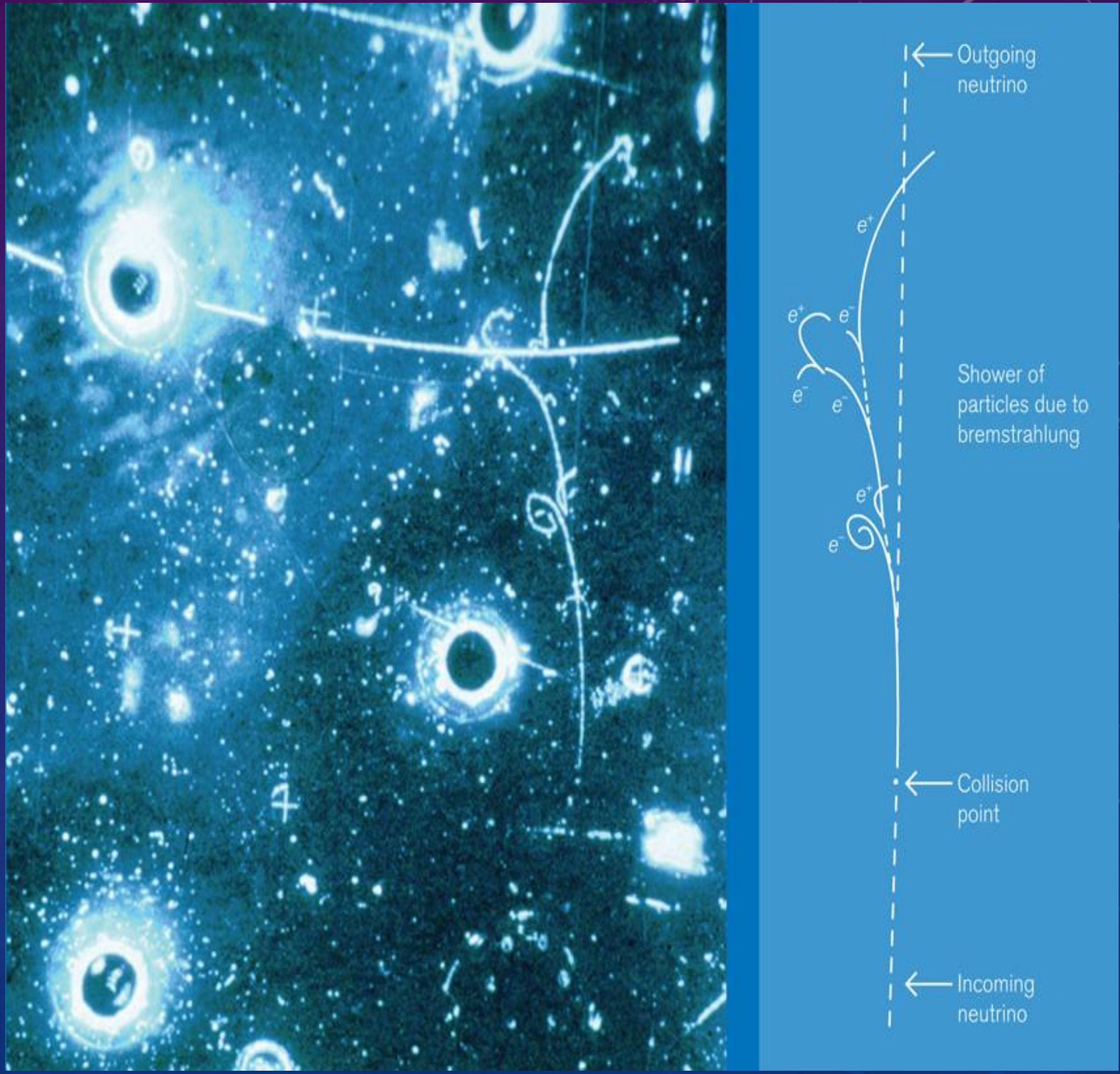
d
d
u
Proton
Neutron

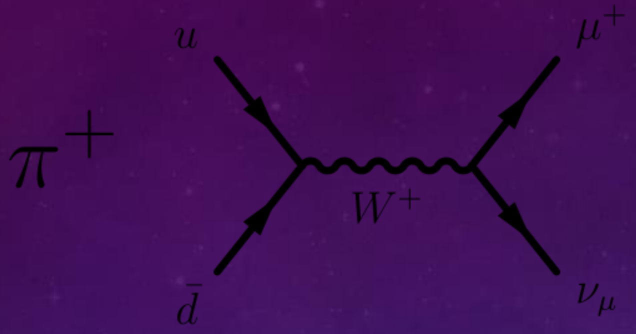
NEUTRAL CURRENTS AND THE ELECTROWEAK INTERACTION

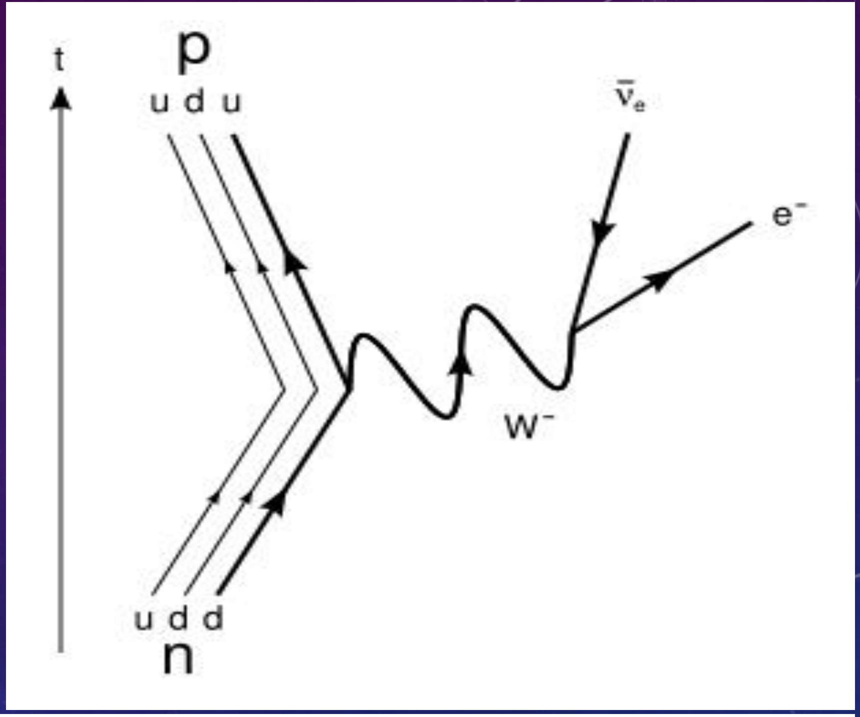
- Neutral current is one of the ways that particles interact via the weak force, an example of neutral current is neutral contribution of $e^- \nu_e \rightarrow e^- \nu_e$elastic cross-section.
- However, Z- boson currents have a distinctive significance as their discovery by CERN 1973 lead to confirmation of electroweak model by Abdul-Salam and Weinberg and The rise of The Standard Model. In addition, they lead to the discovery of W± and Z boson and Quantum Flavourdynamics.

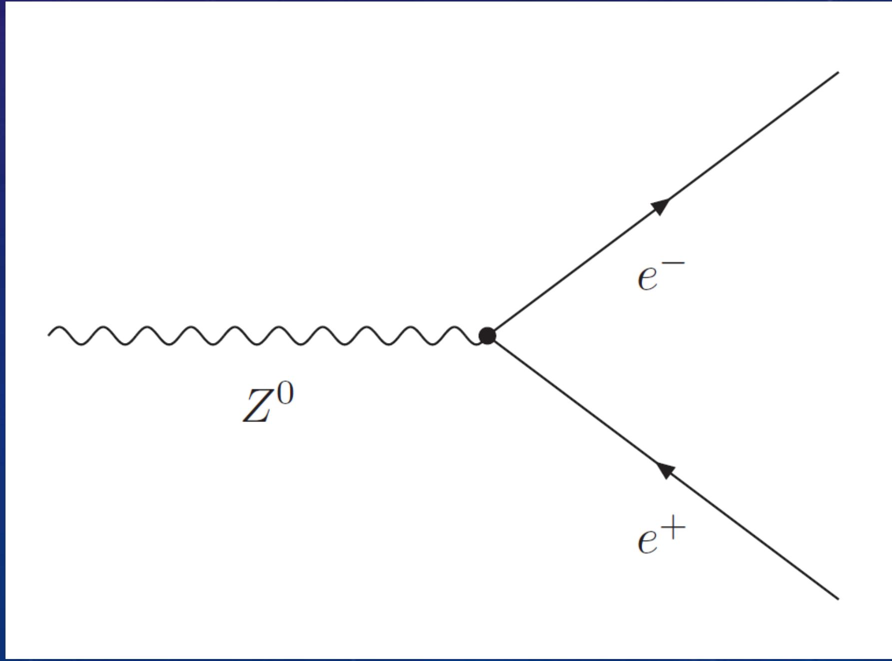
Picture of Gargamelle bubble chamber neutrino experiment weak-current



WEAK INTERACTION







- It is the only interaction capable of changing the flavour of quarks (i.e., of changing one type of quark into another).
- It is the only interaction that violates P or parity-symmetry. It is also the only one that violates CP symmetry. (only Left-Handed particles interact weakly)
- It is propagated by carrier particles (known as gauge bosons) that have significant masses, an unusual feature
- There are two types of weak interactions:

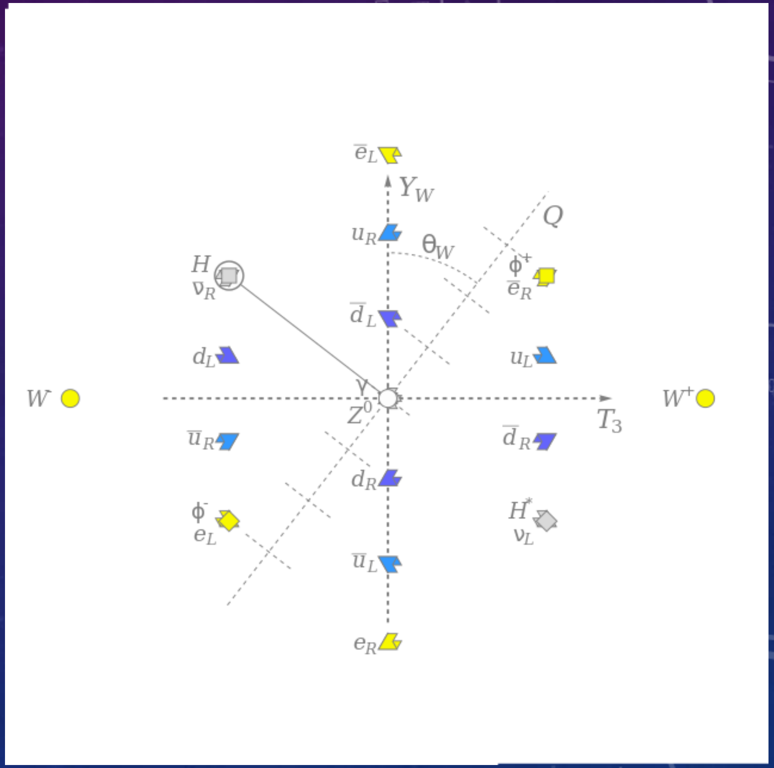
- Charged current interaction (e.g. beta decay)
- Neutral current interaction (e.g. Z-boson decay)

ELECTROWEAK MODEL AND HIGGS MECHANISM

- At Energy of order of magnitude of 100GeV, electromagnetic and weak interactions become indistinguishable. The theory which describes such interaction is called *electroweak* model.
- Mathematically such unification is achieved via SU(2) x U(1) group. With corresponding gauge bosons (W+, W0, and W−) , and the B0 - Weak hypercharge is acquired from U(1) and isospin from SU(2).
- At lower energy, a mechanism postulated by P. Higgs, François Englert *et al* . Predicts existence of a 0-spin scalar field that forms a condensate in all space, knows as the Higgs field. When this field gets a vacuum expectation value (E< 100GeV) spontaneous symmetry breaking occurs described– in short- as the following:

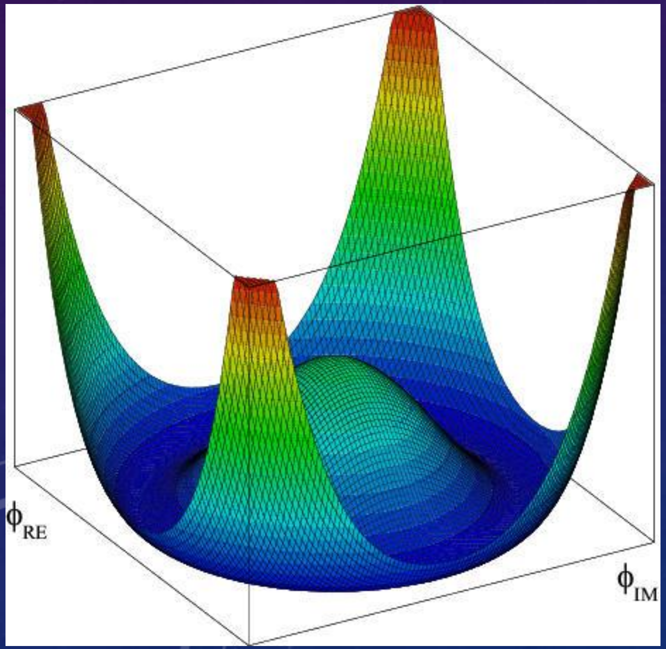
$$\begin{pmatrix} \gamma \\ Z^0 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta \end{pmatrix} \begin{pmatrix} B^0 \\ W^0 \end{pmatrix}$$

where θ_W is the weak mixing angle (Weinberg angle) and defined empirically as $\sin\theta_W = \frac{m_W}{m_Z}$



MORE ON THE HIGGS

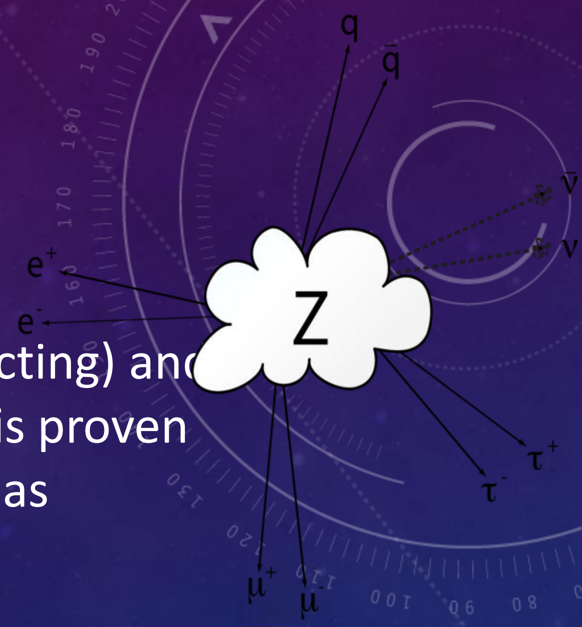
It is useful, for simplicity to think *naively* the symmetry-breaking of EW interaction caused by the non-zero vacuum expectation value of the Higgs, is similar to one we see in optics. Light of different wavelengths travel at different velocities in a prism hence, we see different colours come out of the prism in different angles and dispersion phenomena occurs. Same picture can help imagining Higgs mechanism Z –boson interacts differently which the Higgs than photon (the latter is massless and is very weakly coupled to the Higgs).



The Higgs also gives fermions their masses via Yukawa interaction, example the ith generation of Up and down quarks

$$\mathcal{L}_Y = -\frac{\lambda_u^{ij}(\phi^0 - i\phi^3)}{\sqrt{2}}\bar{u}_L^i u_R^j + \frac{\lambda_u^{ij}(\phi^1 - i\phi^2)}{\sqrt{2}}\bar{d}_L^i u_R^j - \frac{\lambda_d^{ij}(\phi^0 - i\phi^3)}{\sqrt{2}}\bar{d}_L^i d_R^j - \frac{\lambda_d^{ij}(\phi^1 - i\phi^2)}{\sqrt{2}}\bar{u}_L^i d_R^j + hermitian\ conjugate\ terms$$

FINAL FORM OF THE STANDARD MODEL

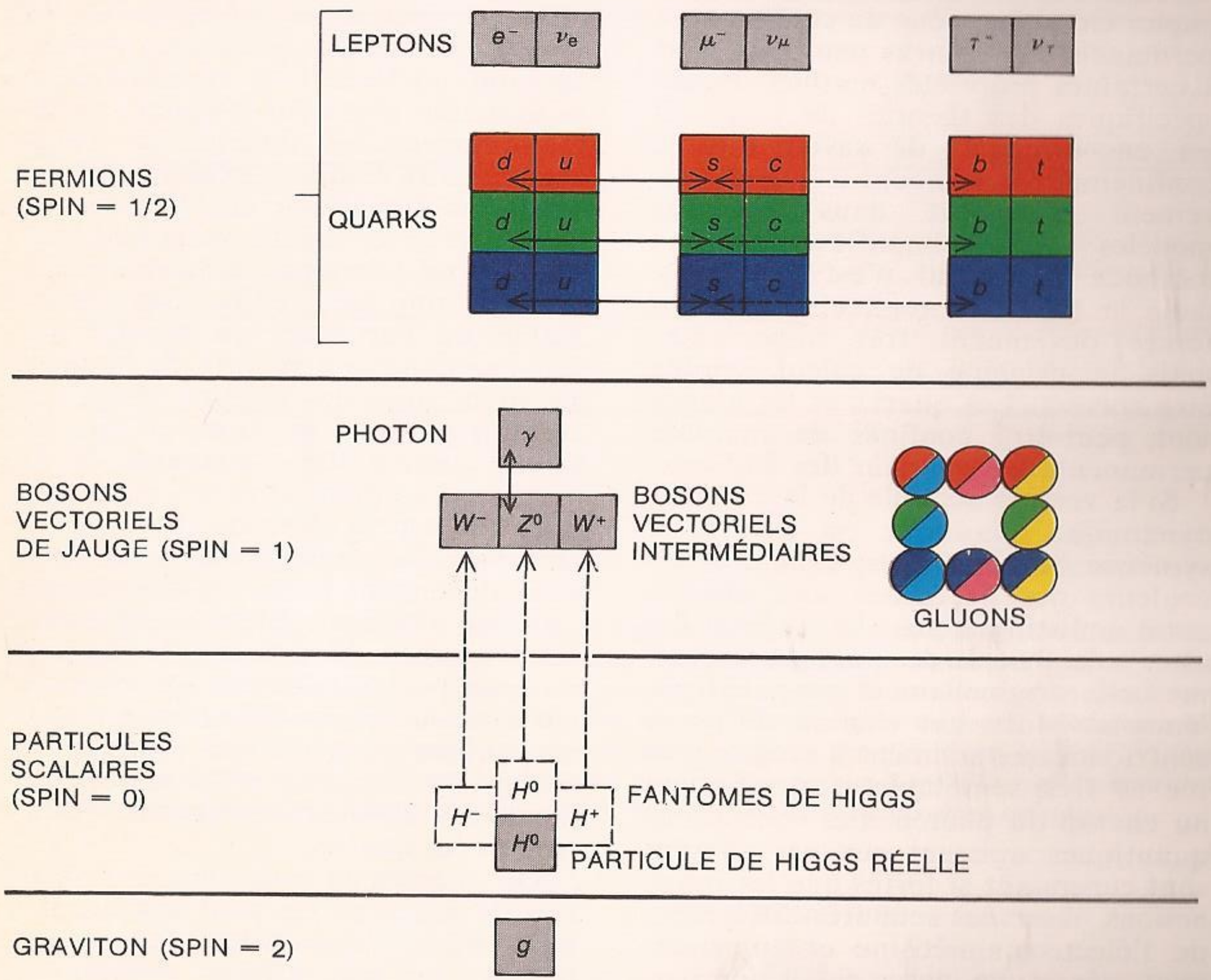


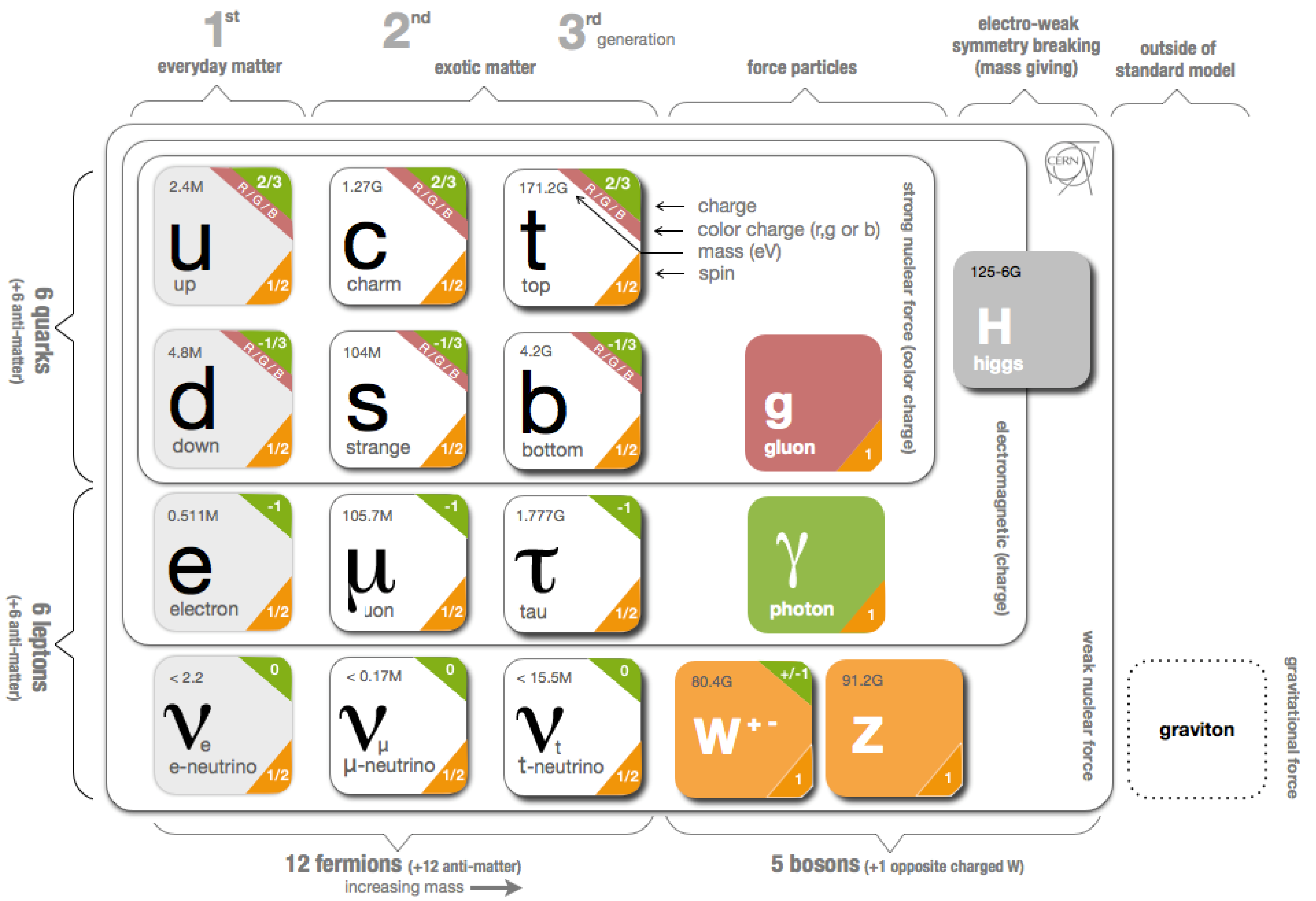
- There are two main types of particles: fermions and bosons.
- Fermions are “matter” particles, there are two types of them: quarks (strongly interacting) and leptons (blind to the strong force). There are ONLY three generations of matter (this is proven due to Z boson decay confirmed by LEP- CERN). There exist another copy of fermions as antimatter .
- There are 12 gauge bosons *(force mediators) and one scalar boson (the Higgs).
- Only left-handed particles interact weakly thus particles are supposed to be massless.
  They acquire mass via coupling to the Higgs field
- Hadrons are strongly interacting composite particles (baryons are made from qqq and measons are made from qq*
- Gravity is not included in the model.

* From the group (U1 × SU2 × SU3) has 12 generators -> under local symmetry we get 12 vector gauge fields and their quanta (gauge bosons)

unifiait l'électricité et le magnétisme

raction forte, l'interaction faible et

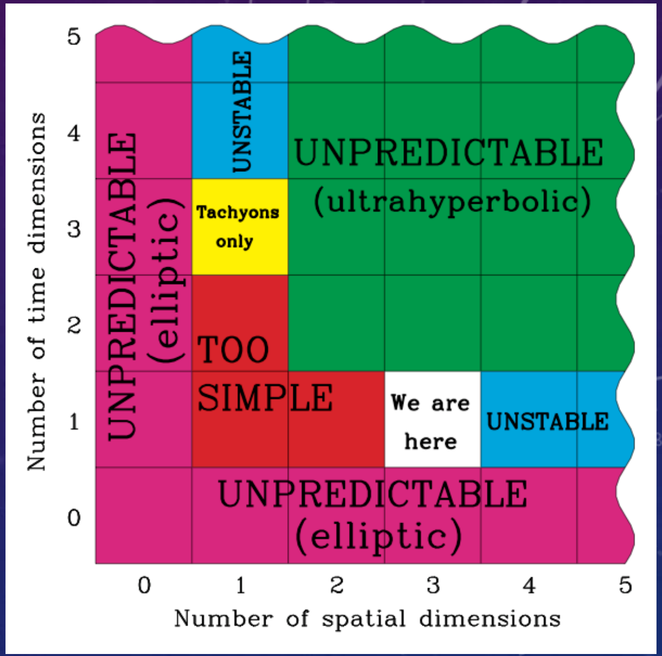


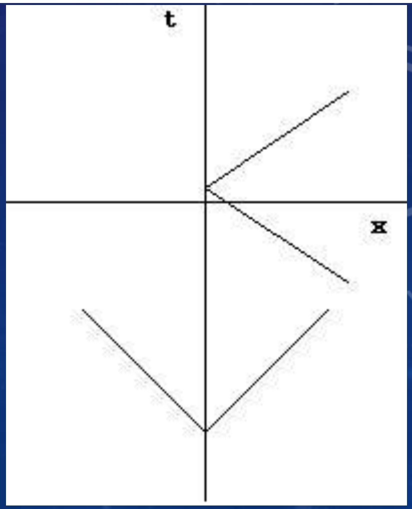


1st everyday matter
2nd exotic matter
3rd generation
force particles
electro-weak symmetry breaking (mass giving)
outside of standard model
6 quarks (+6 anti-matter)
6 leptons (+6 anti-matter)
2.4M u up 2/3 R/G/B 1/2
1.27G c charm 2/3 R/G/B 1/2
171.2G t top 2/3 R/G/B 1/2
charge
color charge (r,g or b)
mass (eV)
spin
4.8M d down -1/3 R/G/B 1/2
104M s strange -1/3 R/G/B 1/2
4.2G b bottom -1/3 R/G/B 1/2
g gluon 1
125-6G H higgs
strong nuclear force (color charge)
electromagnetic (charge)
0.511M e electron -1 1/2
105.7M μ uon -1 1/2
1.777G τ tau -1 1/2
γ photon 1
< 2.2 νe e-neutrino 0 1/2
< 0.17M νμ μ-neutrino 0 1/2
< 15.5M νt t-neutrino 0 1/2
80.4G W+- +/-1 1
91.2G Z 1
weak nuclear force
graviton
gravitational force
12 fermions (+12 anti-matter)
increasing mass
5 bosons (+1 opposite charged W)

IS IT COMPLETE ? BEYOND THE STANDARD MODEL

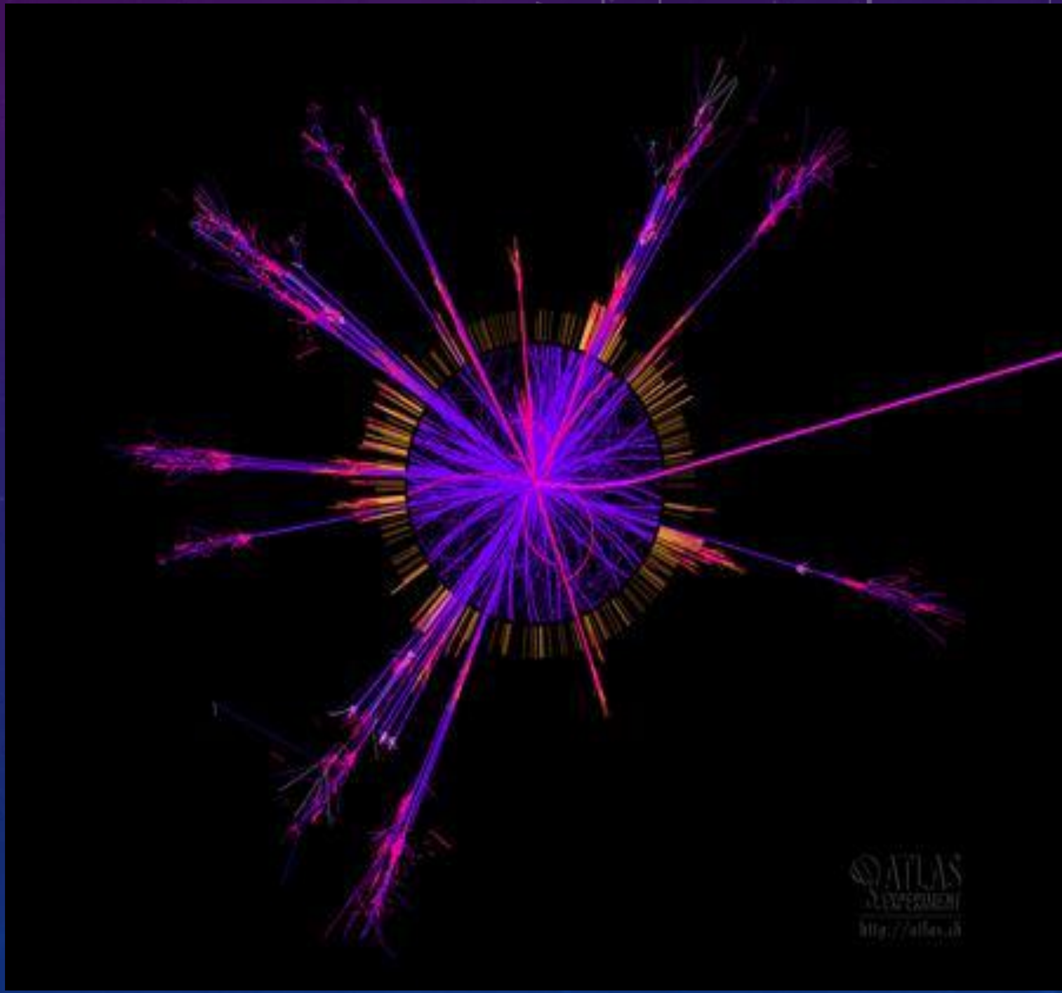
- The standard model is certainly the most successful theory humanity ever had to describe the universe. It is mathematically consistent and experimentally verified in many ways.
- Nevertheless, the theory is not a complete description of nature. There are so many question that the SM cannot answer:
  - Grand Unified Theories (GUT)
  - Baryogenesis
  - Supersymmetry (SUSY)
  - Dark matter and Dark Energy
  - Quantum Theory of Gravity
  - Unified Field Theories.
  -why 3+1 dimensions ?
  … and many more!
  All are beyond the standard model.
- The SM is a very good description of nature at the level of 0.001fm ~100 GeV but what goes beyond faces both experimental and theoretical difficulties.
- Ordinary matter only forms ~4 % of the universe !





WHAT ARE THE APPROACHES BEYOND THE STANDARD MODEL.

- GUT had theoretical difficulties in the past with SU(5) and proton decay*. Now with SO(10) it’s believed that we have consistent model
- Many problems can be solved by SUSY, like hierarchy problem of the nature of dark matter .
- CERN had models for a micro-black holes (researches showed that if they exist they could lead to the discovery of higher dimensions.
- Maybe the models beyond SM could be more mathematically elegant.
- Alpha experiment in the LHCb is considering the matter-antimatter asymmetry.
- We are still far from consistent, testable Quantum theory of Gravity.
- Superstring theories and M-Theory are untestable by our technology.



*Virtual blackholes (Hawking, 1995) can provide a solution to the proton decay mechanism that is needed for many GUT’s.

THANK YOU !

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