# Introduction to Particle Physics

# Basics

Particle Physics describes the basic constituents of matter

and their interactions

It has a deep interplay with cosmology

Modern cosmology and PP's are complementary in our quest to answer the basic riddles in our current understanding of the Universe

There is no point in following a historical introduction in a one hour talk

# Tools

Special Relativity

Quantum Mechanics

Quantum Field Theory

General Relativity

# Special units

$$\hbar = \frac{h}{2\pi} = 1 \qquad c = 1 \qquad k = 1$$

$$\begin{aligned} 1\,\mathrm{eV} &= 1.602 \times 10^{-12}\ \mathrm{ergs} \\ 1\,\mathrm{keV} &= 10^{3}\,\mathrm{eV} \\ 1\,\mathrm{MeV} &= 10^{6}\,\mathrm{eV} \\ 1\,\mathrm{GeV} &= 10^{9}\,\mathrm{eV} \\ 1\,\mathrm{TeV} &= 10^{12}\,\mathrm{eV} \end{aligned}$$

Everything is expressed in terms of either length or energy. Measure time in centimeters, x0 = c t. We can measure energy in grams, or mass in MeVs

The electron mass is 0.511 MeV

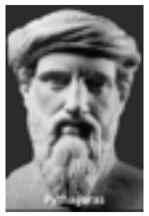
$$L \sim \frac{1}{E} \qquad E \sim \frac{1}{L}$$

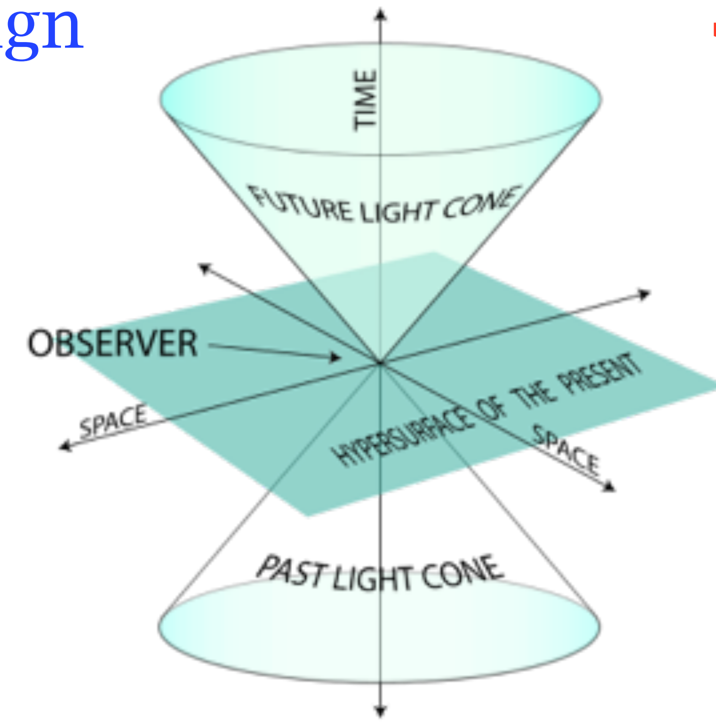
The proton mass is about 1 GeV

The LHC will run at 13.5 TeV

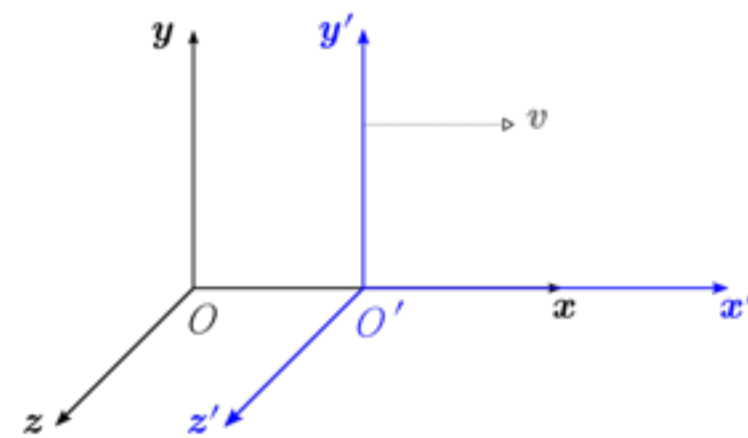
# Special relativity

## Pythagoras with a minus sign



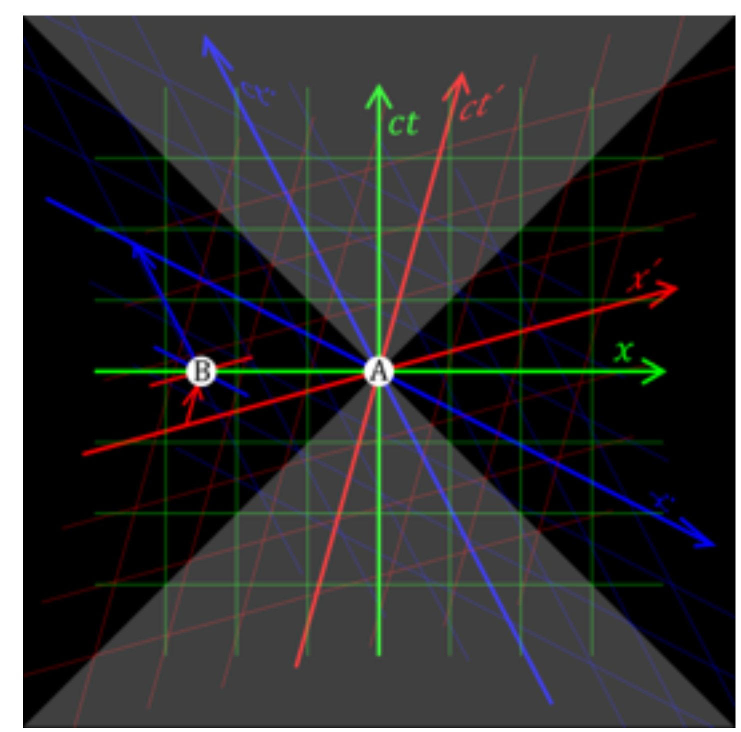



$$(\Delta L)^2 = (\Delta x)^2 + (\Delta y)^2$$
$$(\Delta \tau)^2 = (\Delta t)^2 - (\Delta x)^2$$




$$\begin{aligned} t' &= \gamma\,(t - \frac{v\,x}{c^2}) \\ x' &= \gamma\,(x - v\,t) \\ y' &= y \\ z' &= z \end{aligned}$$

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$




$$(E, p_x, p_y, p_y)$$

$$E^2 = \mathbf{p}^2 + m^2$$

# Einstein's 1st equation

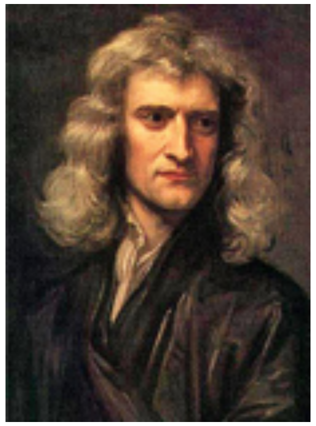
$$E = m c^2$$

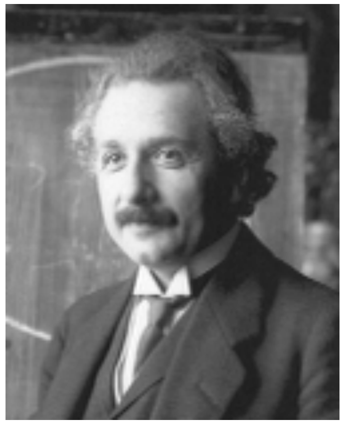
# Einstein's 2nd equation

$$m = \frac{E}{c^2}$$

Particle numbers are not conserved. Energy can be converted into particles and vice versa. This is the great difficulty with QM and Relativity. It is also the origin of the existence of antimatter

Mechanics reminder





$$p_N = m\,v$$

$$p_E = m\,v\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$E_N = \frac{m}{2}\,v^2$$

$$E_E = m\,c^2\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

$$m \to 0, \qquad v \to c \qquad p = \frac{E}{c}$$

Mass (inertia) represents resistance to acceleration

Nothing to do with friction

Viscosity is resistance to velocity

# Quantum mechanics

The dynamical state of a system is described by the wave function of the system, a probability amplitude, which satisfies the Schroedinger equation.

$$\Psi(\mathbf{r_1}, \mathbf{r_2} \ldots, \mathbf{r_n}, t)$$

$$i\,\hbar\,\frac{\partial}{\partial t}\Psi(\mathbf{r_1}, \mathbf{r_2} \ldots, \mathbf{r_n}, t) = (\sum_i (-\frac{1}{2\,m_i}\nabla_i^2) + V(\mathbf{r_1}, \mathbf{r_2} \ldots, \mathbf{r_n}, t))\Psi(\mathbf{r_1}, \mathbf{r_2} \ldots, \mathbf{r_n}, t)$$

The space of states is complex

The number of particles is conserved (no particle creation)

Uncertainty relations

Very successful description of the structure of matter in the non-relativistic limit

$$\Delta\,x\,\Delta\,p \geq \frac{\hbar}{2} \qquad \Delta\,t\,\Delta\,E \geq \frac{\hbar}{2}$$

# Quantum field theory

Relativistic invariance

Quantum mechanics

Particle creation

Infinite number of degrees of freedom

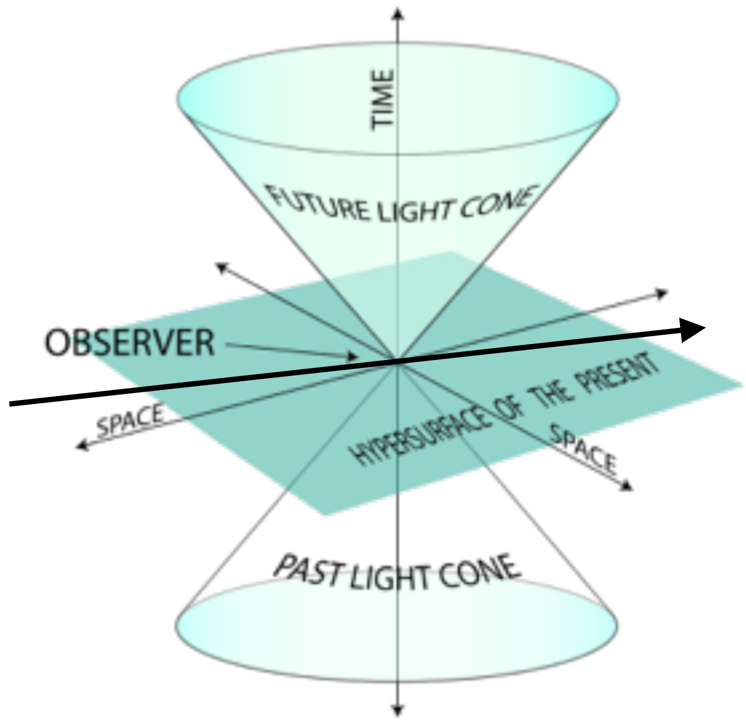
At least one per space point

Wave particle duality, for each field their is a particle (and its anti-particle)

Microscopic causality

The most basic language to express the laws of nature.

The basic problem is to determine the "vacuum", i.e. the state of minimum energy of the universe.  Completely different from the "nada" in classical philosophy.



# General procedure

Kinematics

Dynamics

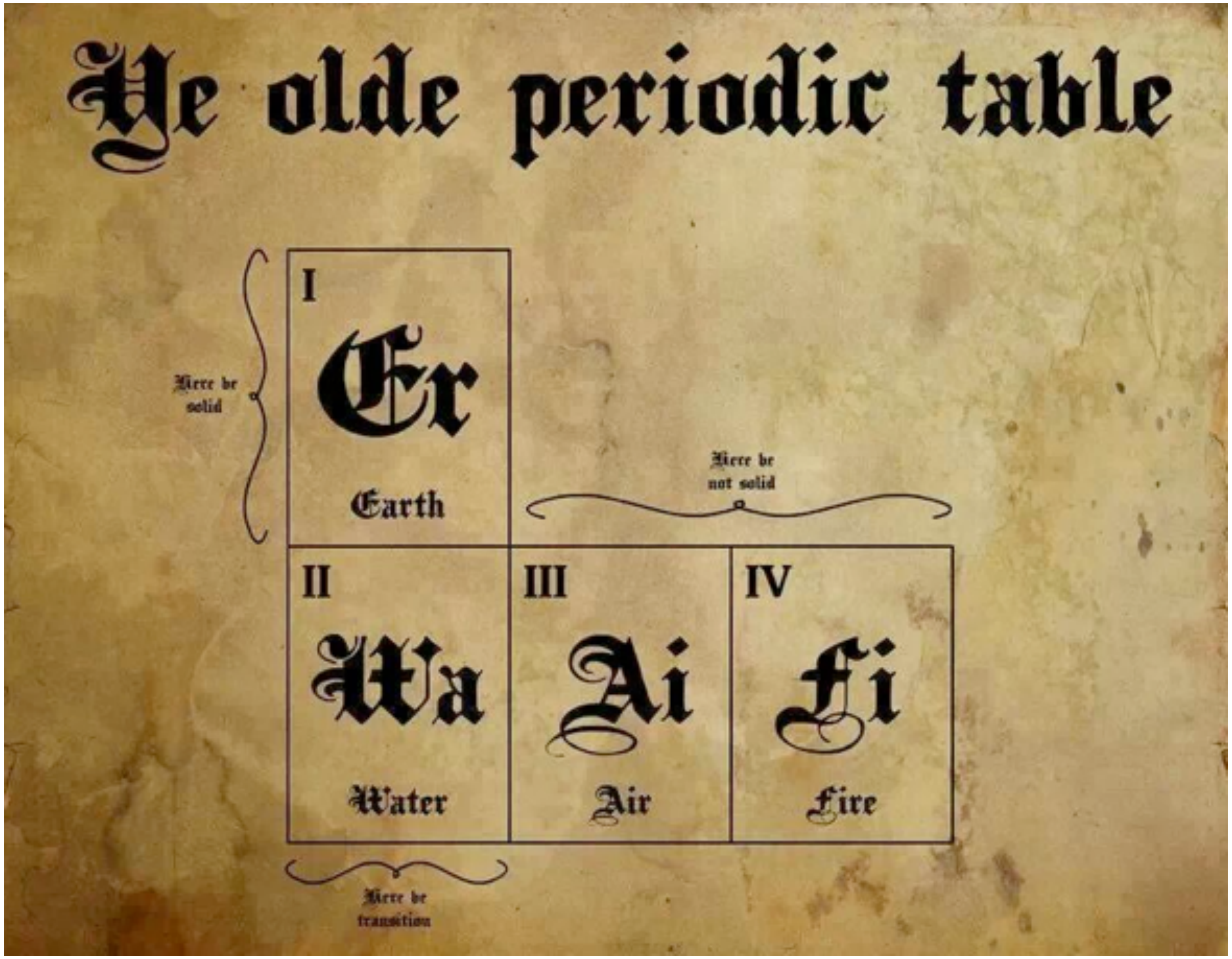
Symmetries

Global, local

Explicit or broken

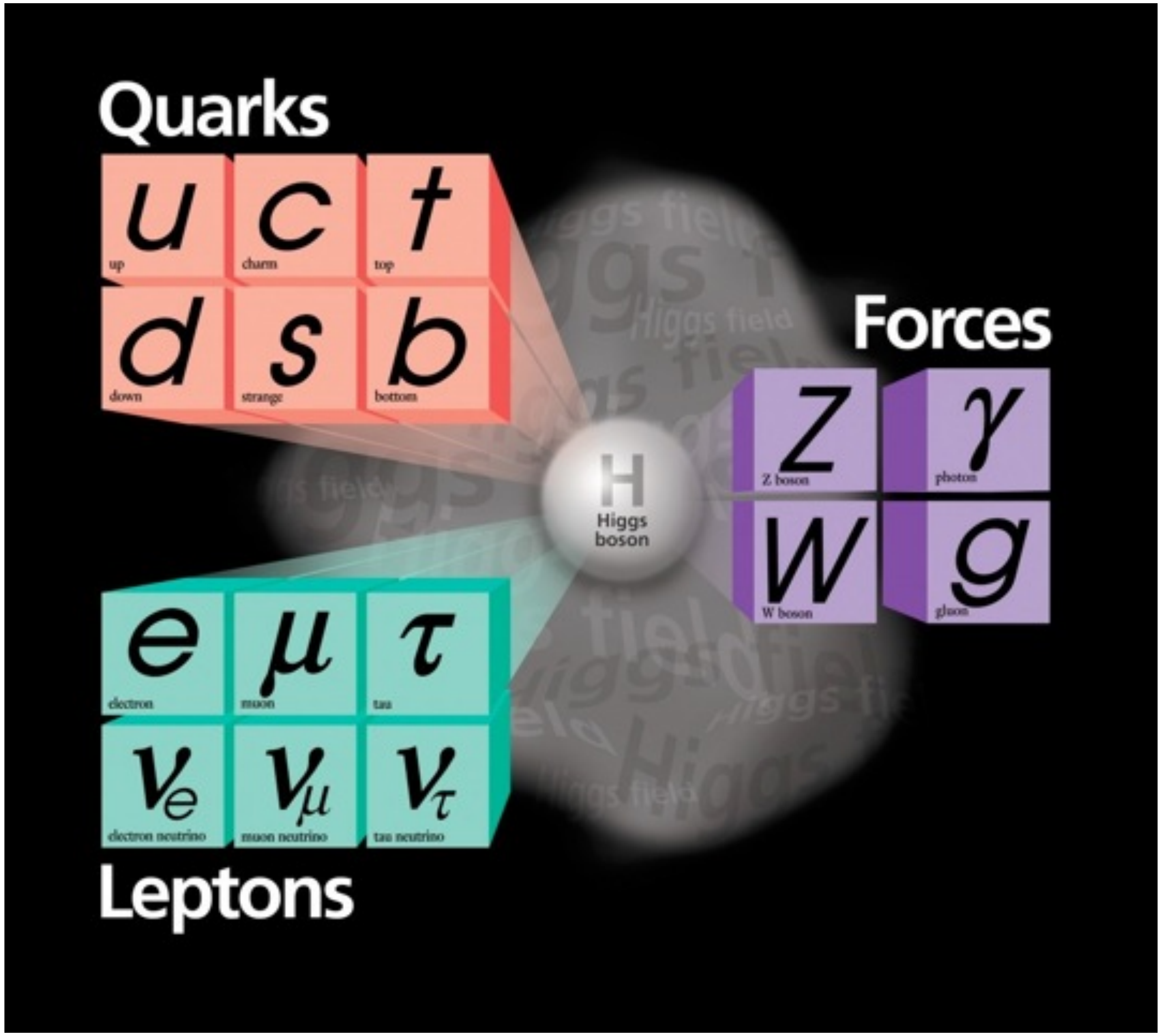
Discrete: Parity, C, T

# Before chemistry

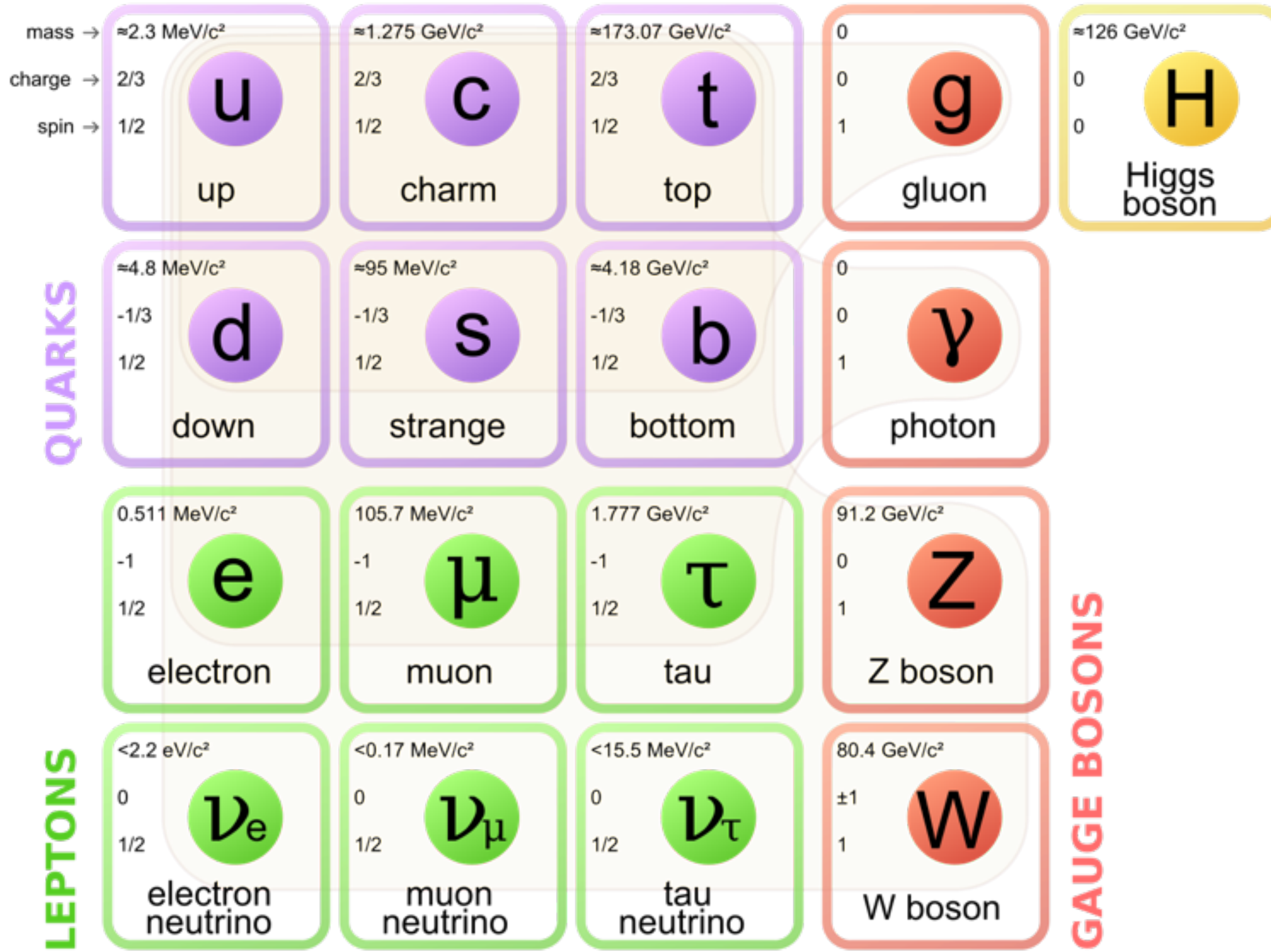


# A more modern one

# Our current table




Each quark comes in three colours. There are three generations of quarks and leptons. All matter we see around us is made of the first generation… the last to come is H!


mass →
charge →
spin →
≈2.3 MeV/c²
2/3
1/2
u
up
≈1.275 GeV/c²
2/3
1/2
c
charm
≈173.07 GeV/c²
2/3
1/2
t
top
0
0
1
g
gluon
≈126 GeV/c²
0
0
H
Higgs boson
≈4.8 MeV/c²
-1/3
1/2
d
down
≈95 MeV/c²
-1/3
1/2
s
strange
≈4.18 GeV/c²
-1/3
1/2
b
bottom
0
0
1
γ
photon
QUARKS
0.511 MeV/c²
-1
1/2
e
electron
105.7 MeV/c²
-1
1/2
μ
muon
1.777 GeV/c²
-1
1/2
τ
tau
91.2 GeV/c²
0
1
Z
Z boson
<2.2 eV/c²
0
1/2
$\nu_e$
electron neutrino
<0.17 MeV/c²
0
1/2
$\nu_\mu$
muon neutrino
<15.5 MeV/c²
0
1/2
$\nu_\tau$
tau neutrino
80.4 GeV/c²
±1
1
W
W boson
LEPTONS
GAUGE BOSONS

# Two types of particles

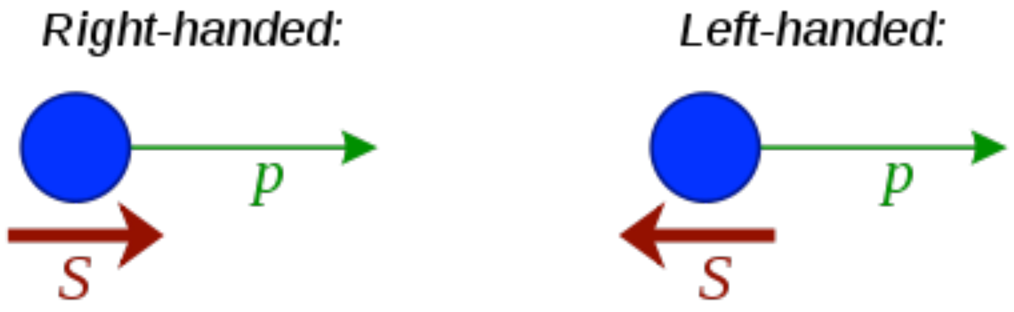
Bosons, integer spin. Very sociable. They admit a classical description. The standard force fields are described by bosons

Fermions half integer spin. Completely asocial. They make atoms and all matter we see around us

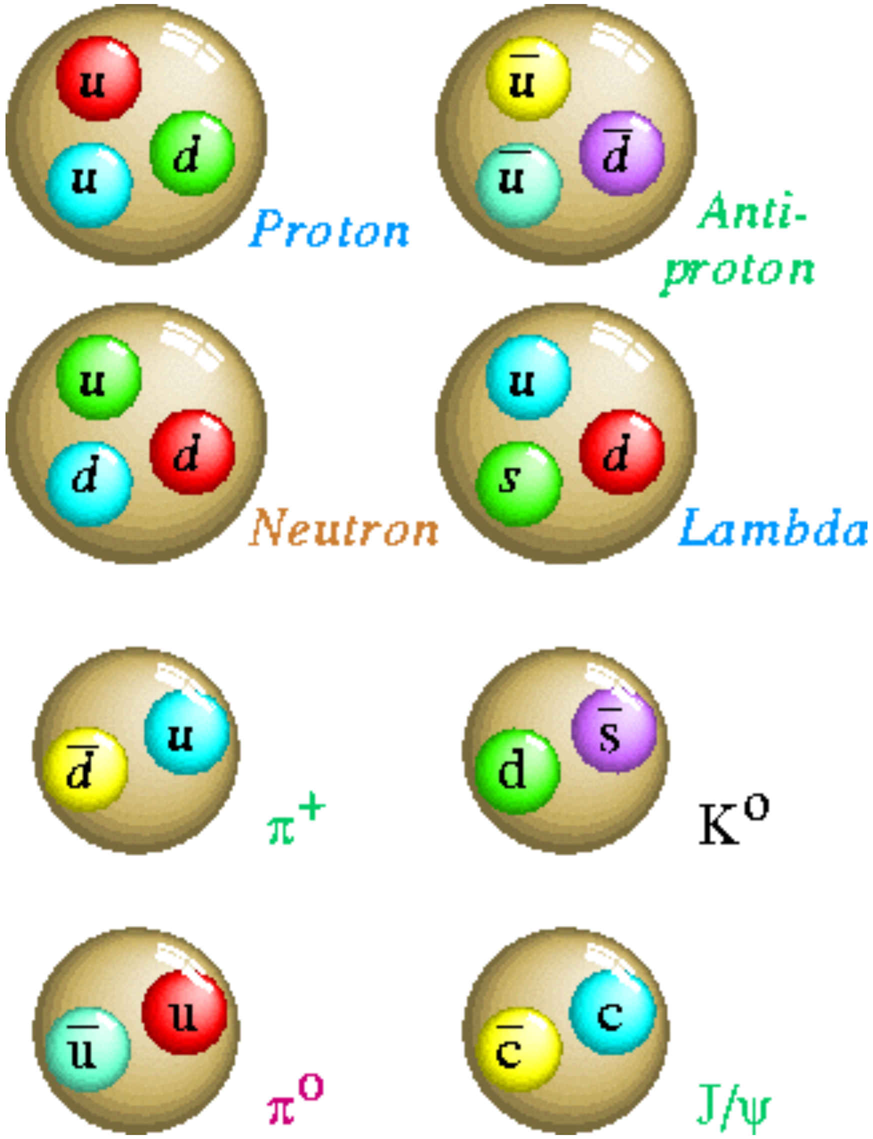
What makes dark matter?

What entity is dark energy?

Why there is no antimatter?



# Hadrons and nuclei are built with quarks

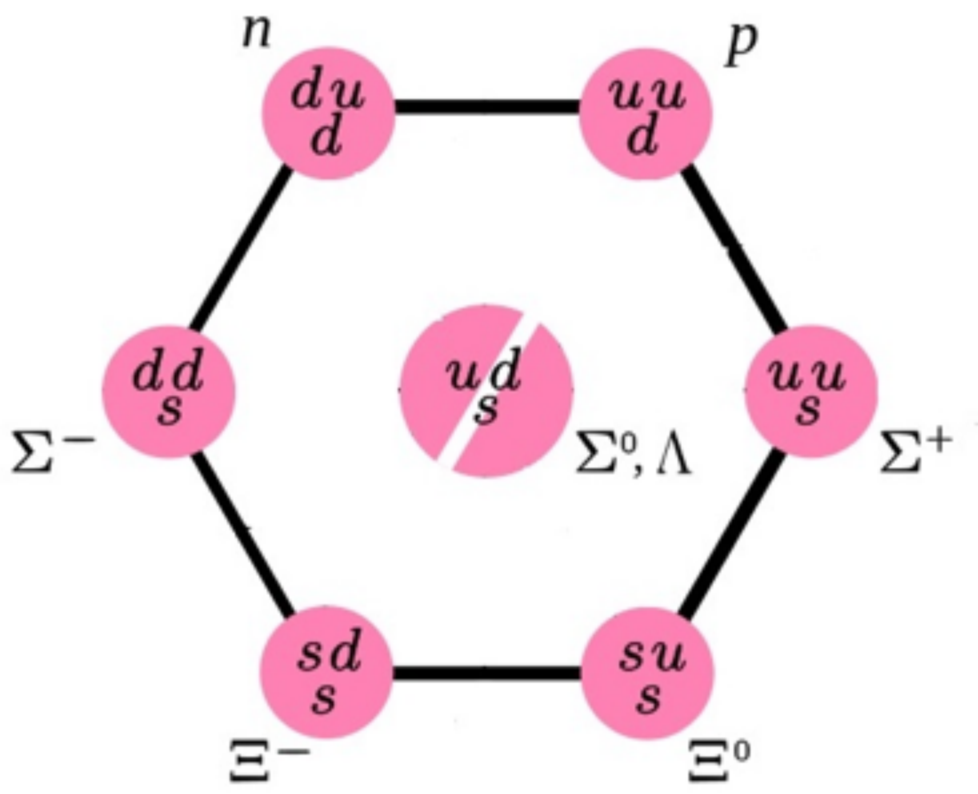


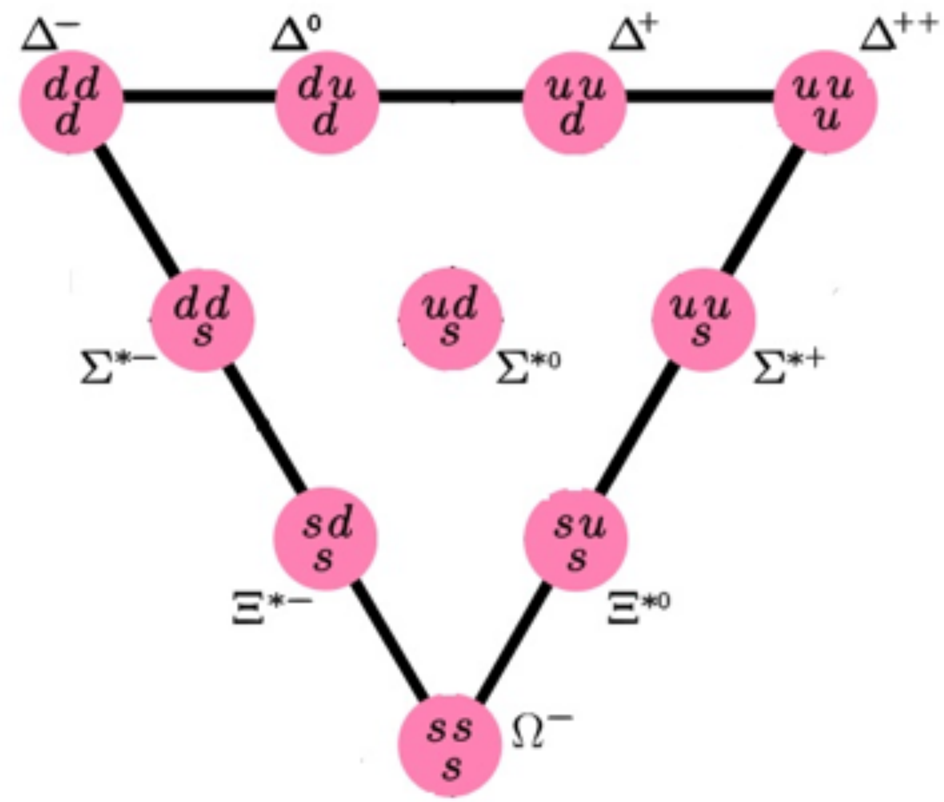

Hadrons come in two varieties:

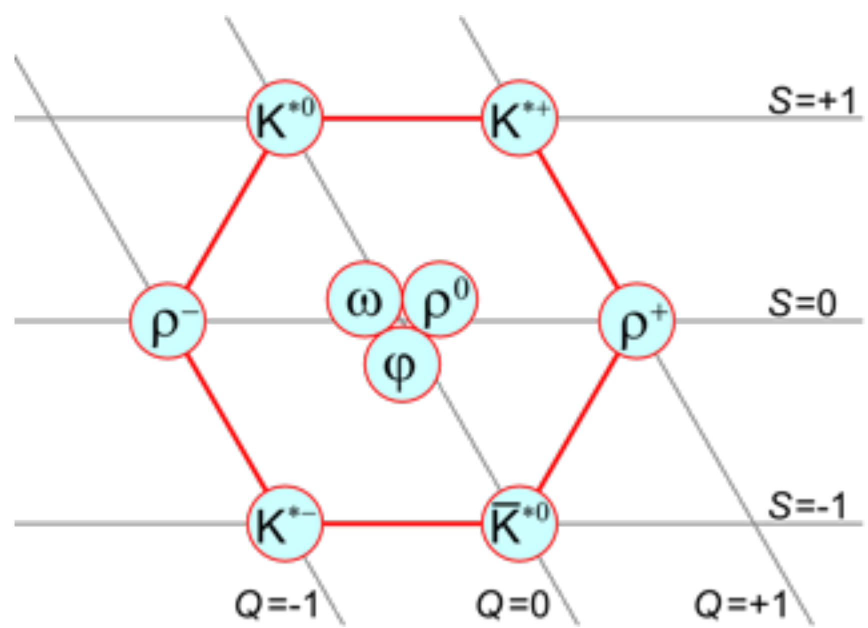
Baryons

Mesons

# Lowest lying baryons and mesons



# Three types of interactions

Electromagnetic

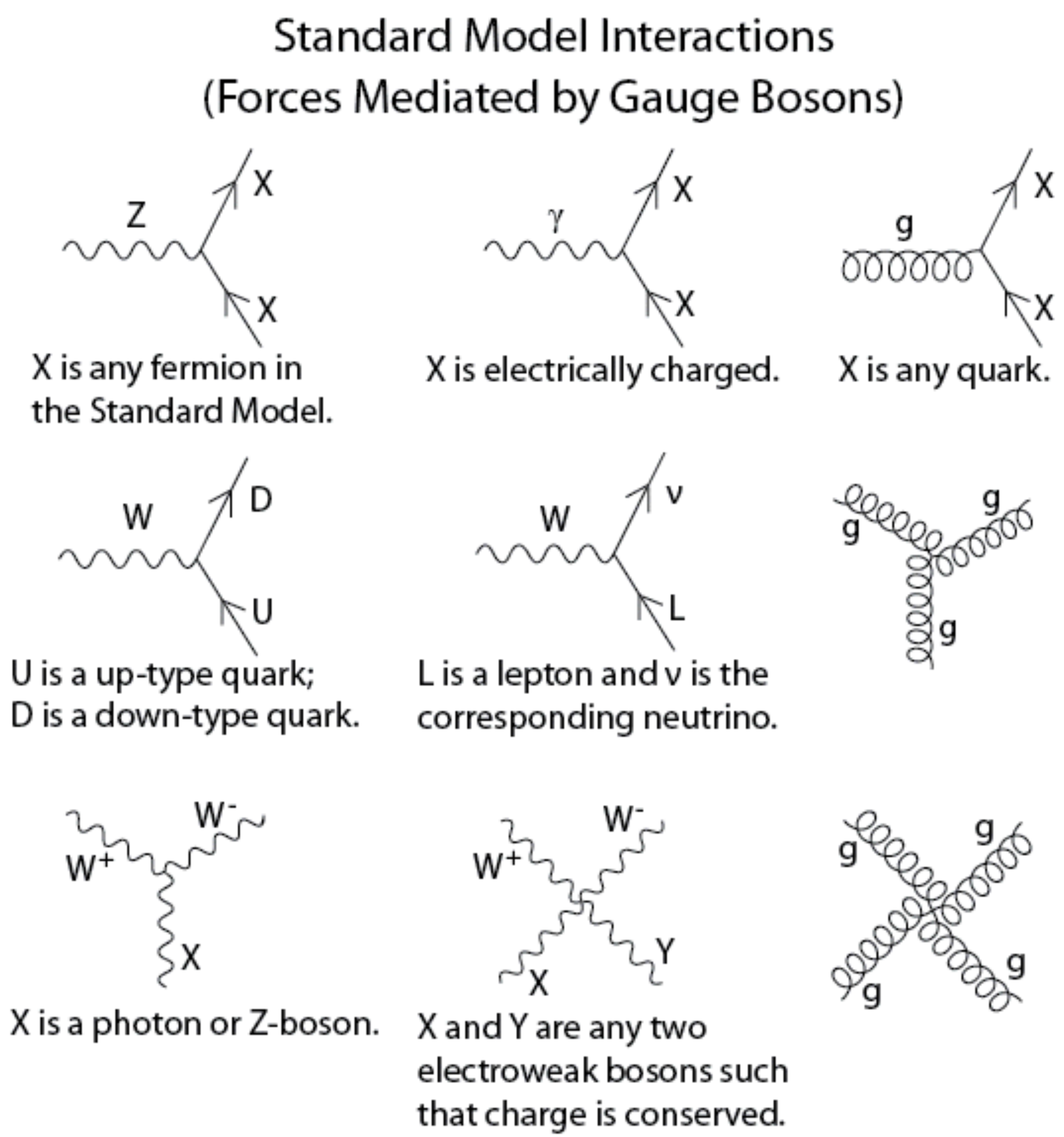
Weak

Strong

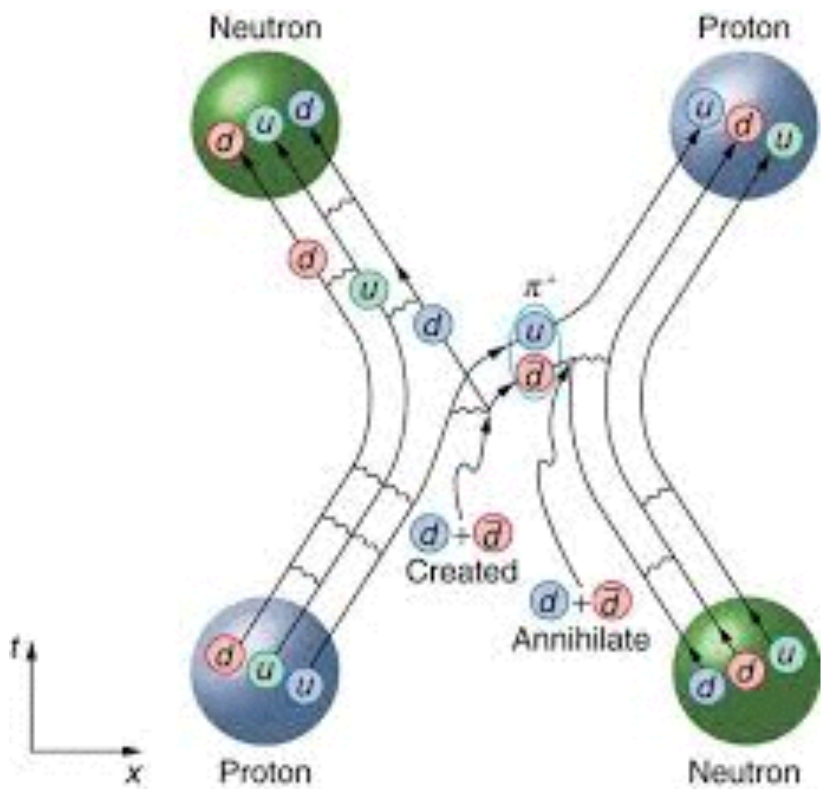
All described by a similar mathematical structure, known as gauge symmetry or gauge invariance

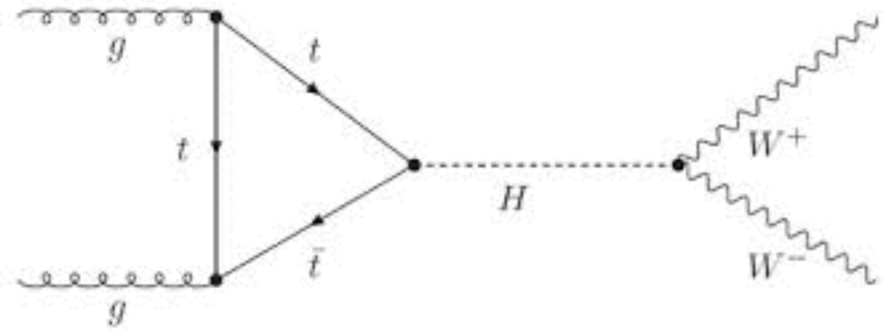
A visual description in terms of Feynman graphs

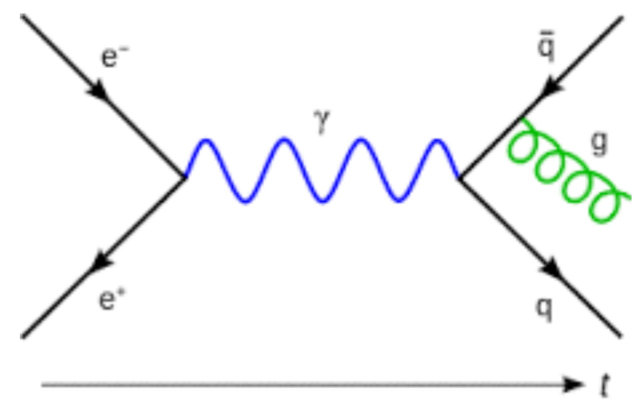
# Precise computational rules

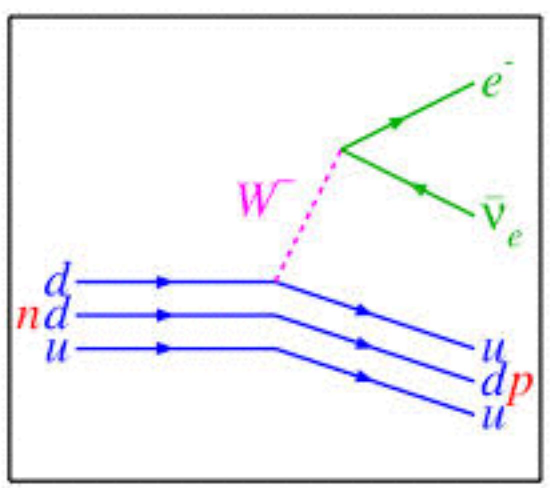


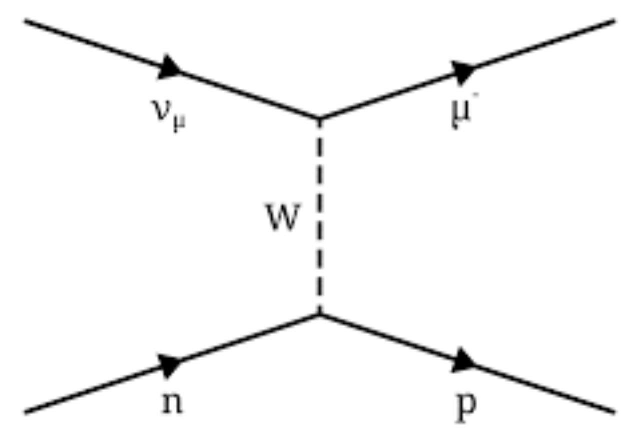
# Some processes…



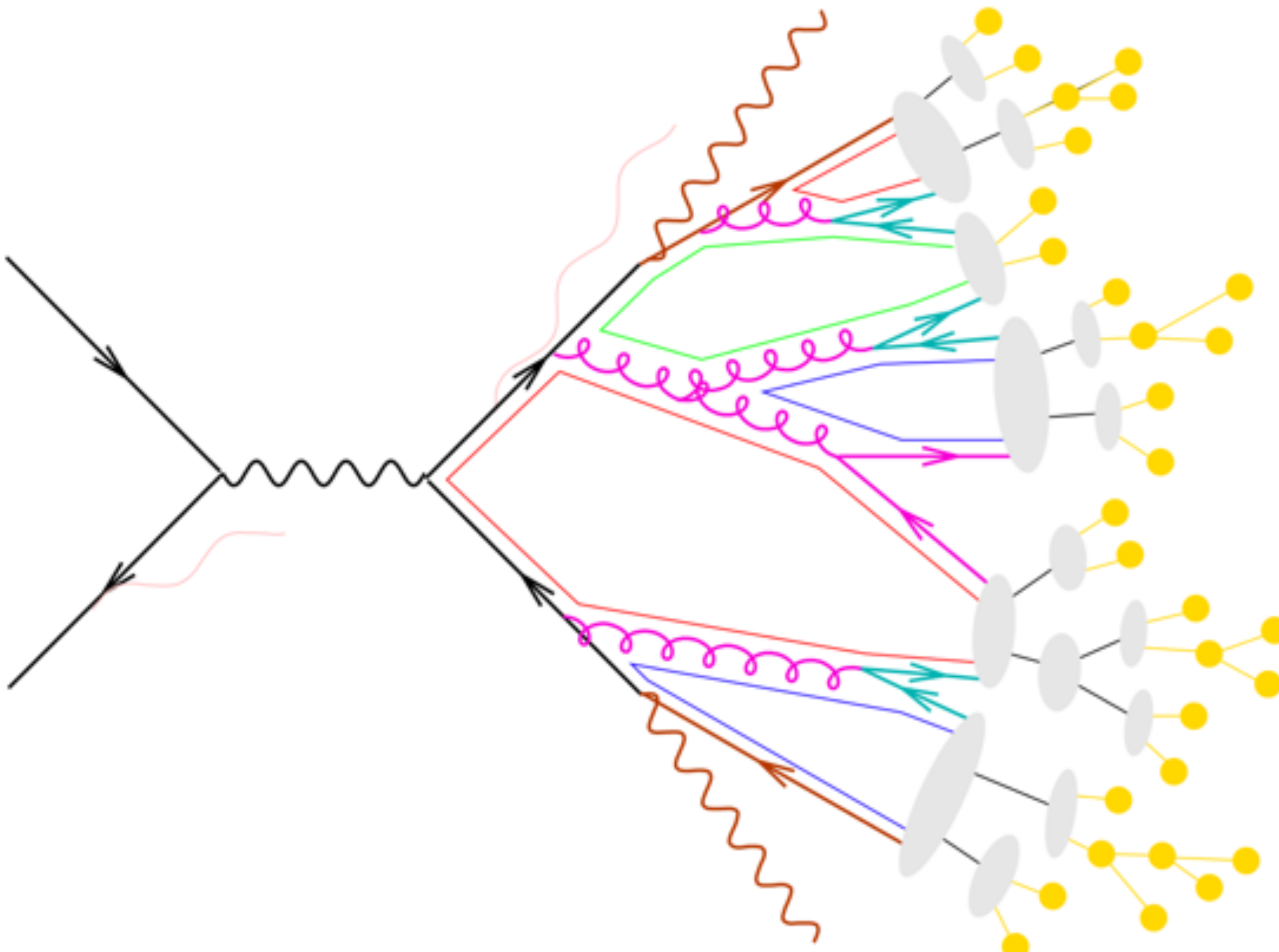



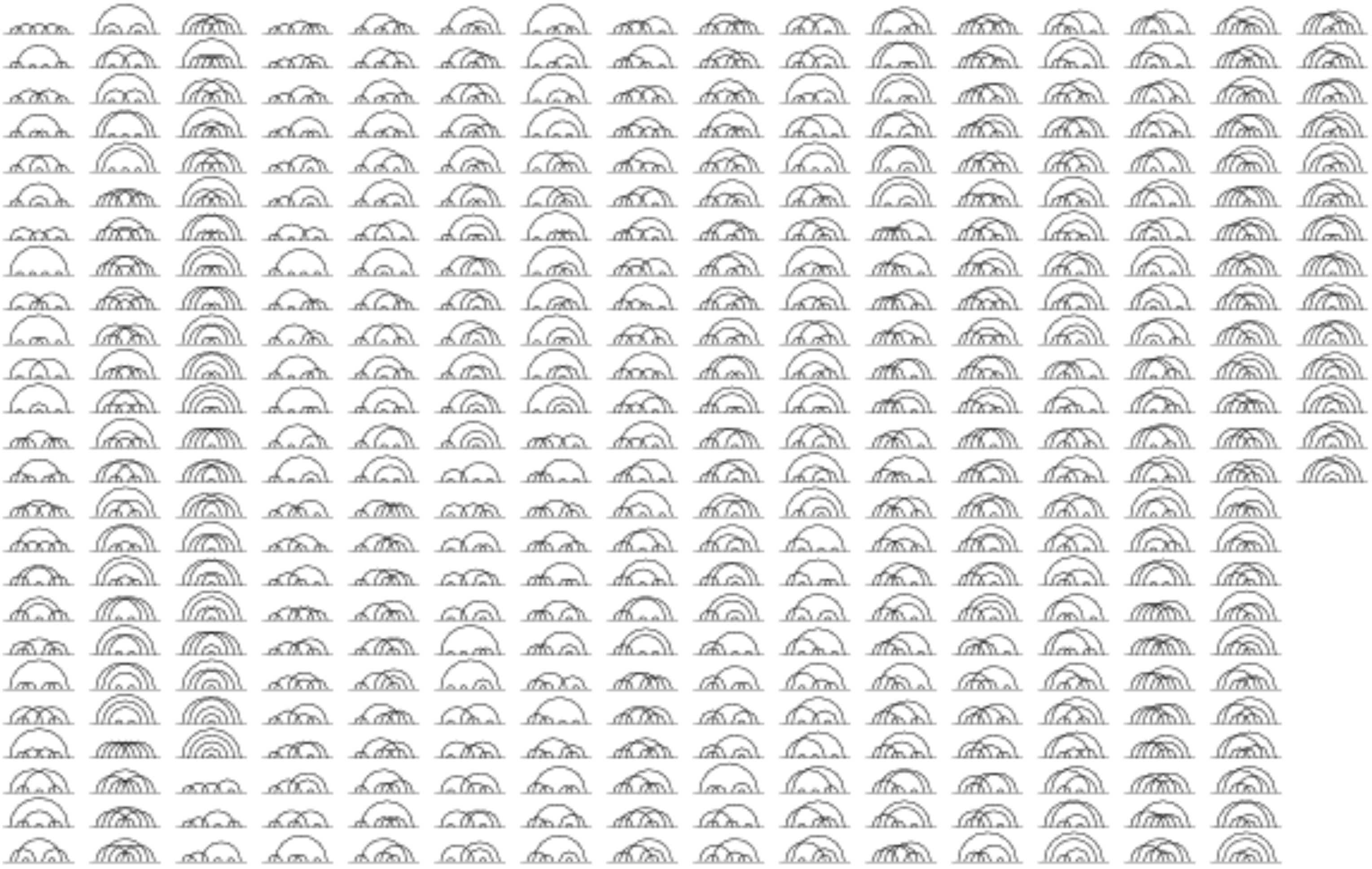



# Some more…



- hard scattering
- (QED) initial/final state radiation
- partonic decays, e.g. $t \rightarrow bW$
- parton shower evolution
- nonperturbative gluon splitting
- colour singlets
- colourless clusters
- cluster fission
- cluster $\rightarrow$ hadrons
- hadronic decays

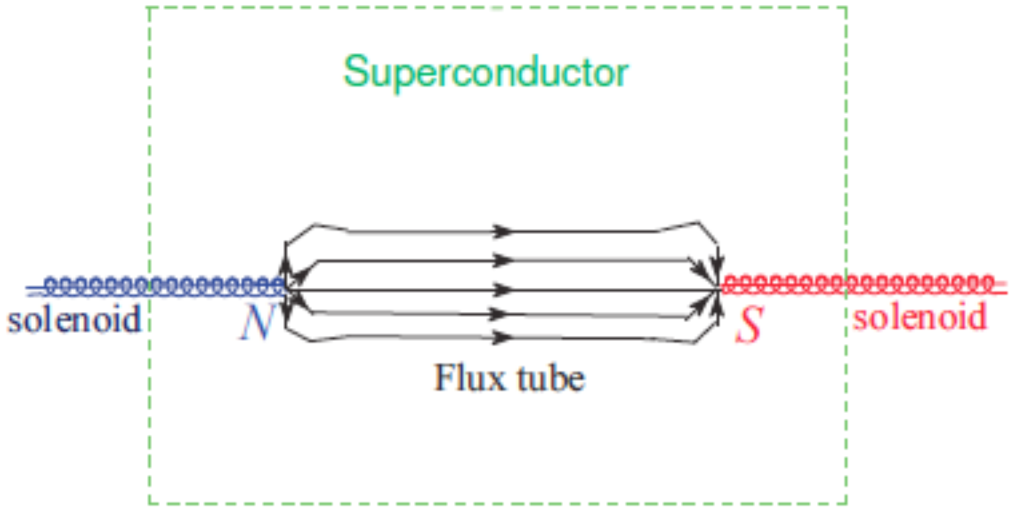
# Sometimes it can be messy…



# Some interesting properties

The strong interactions are mediated by the exchange of gluons. The remarkable property is that all objects carrying colour are confined. The theory, QCD is asymptotically free, but is afflicted with infrared slavery. It happens even if quarks are massless!

This is a purely quantum phenomenon. Similar to the Meissner effect in type II superconductors. In fact, this is the origin of your mass. It is completely mind boggling.




$$E = \sigma L$$

# The Higgs mechanism, how much does it contribute to your weight?


The mass parameters obtained for the light quarks are too small to explain the masses of protons and neutrons that make up nuclei. From elementary nuclear physics we know:

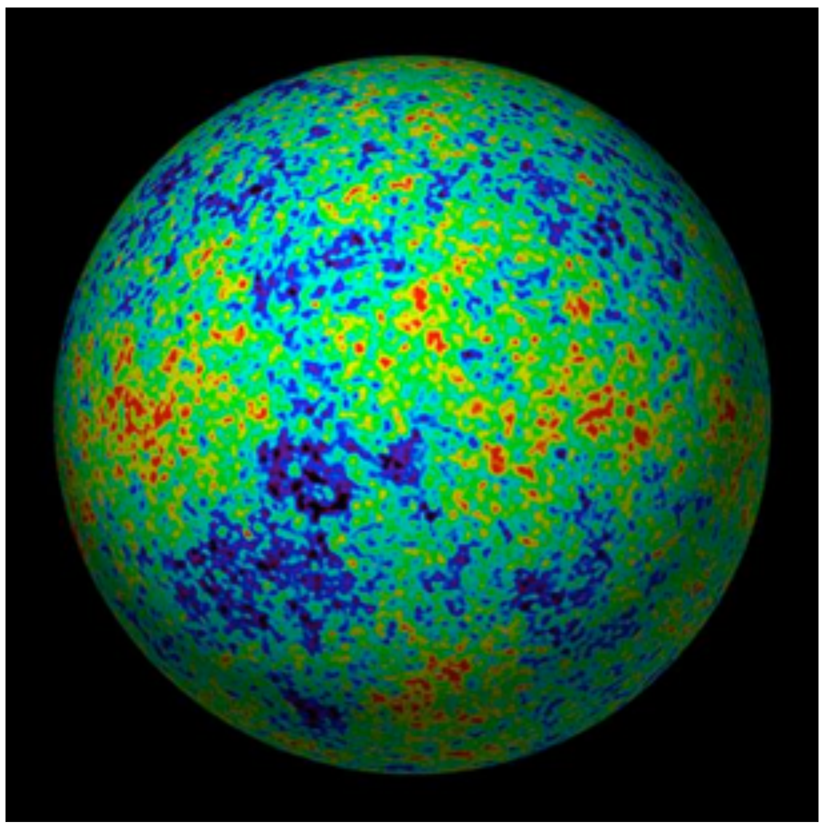
$$M(Z,A) = Z\,m_p + (A-Z)\,m_n + \Delta M(Z,A) \qquad \Delta M(Z,A) << M(Z,A)$$

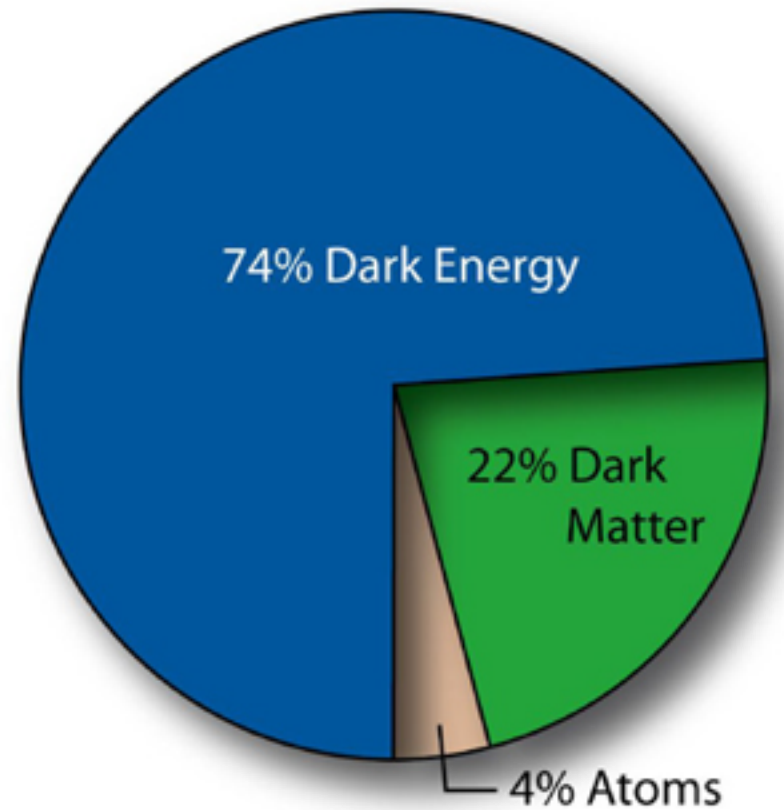
The largest contribution come from the fact that quarks and gluons are highly relativistic objects confined in a space of the order of a fermi. A purely quantum phenomenon due to QCD: the confinement of colour. A new scale is generated dynamically. Generated with the breaking of scale invariance. Most of the mass of nucleons come from this. Even if the mass parameters of the u,d quarks was set to zero, we would still have nucleons. What makes the study of the strong interactions hard is the fact that:

$$\Lambda >> m_u,\, m_d$$

A large fraction of our mass has its origin in this quantum phenomenon of confinement. We are indeed macroscopic quantum objects! There is also a beautiful analogy with the BEH mechanism, but of a more subtle type.

# An unexpected result

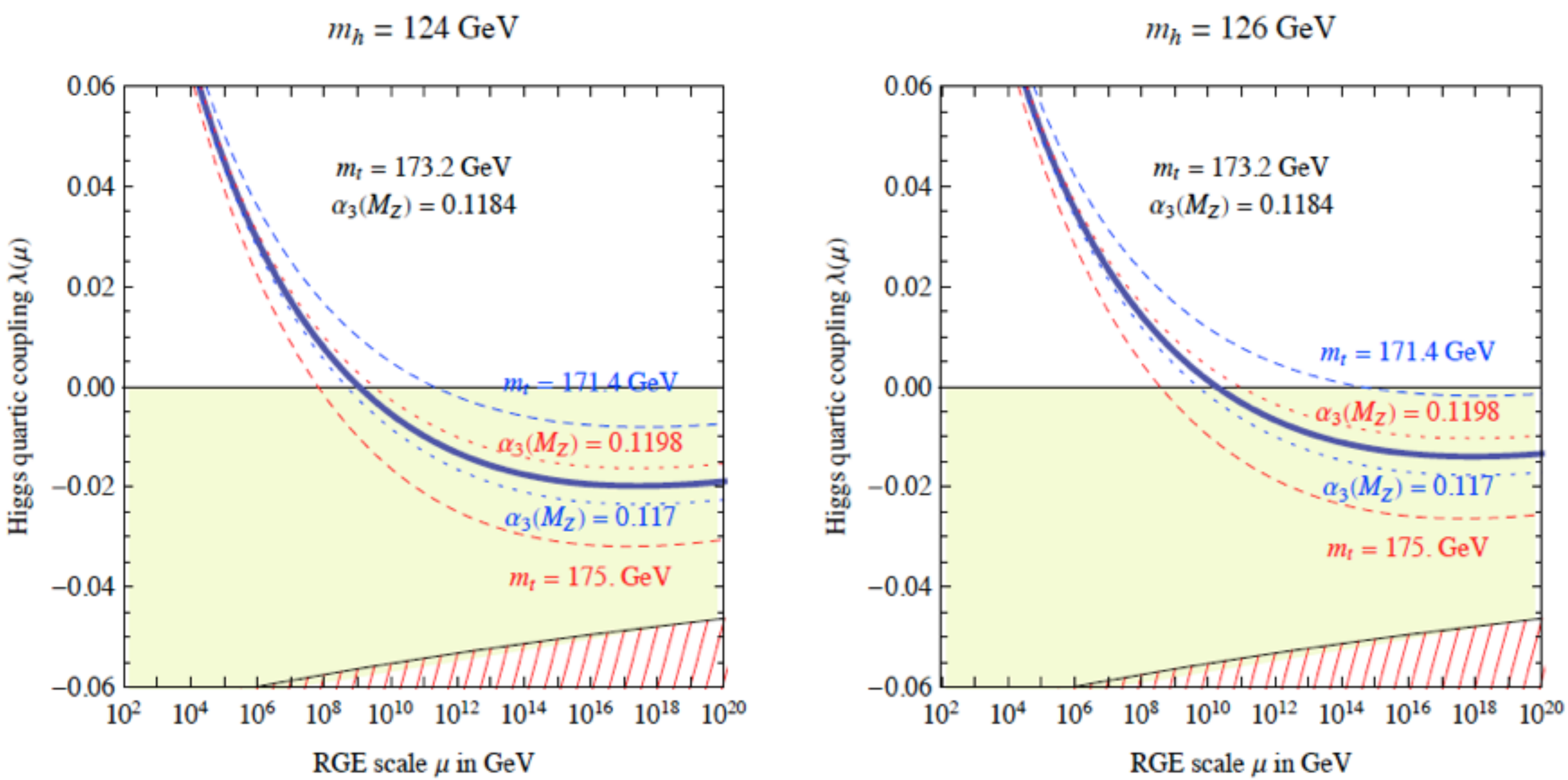





Is it all BEH?

# Another unexpected result

The Planck chimney



$m_h = 124$ GeV
$m_h = 126$ GeV
$m_t = 173.2$ GeV
$\alpha_3(M_Z) = 0.1184$
$m_t = 171.4$ GeV
$\alpha_3(M_Z) = 0.1198$
$\alpha_3(M_Z) = 0.117$
$m_t = 175.$ GeV
Higgs quartic coupling $\lambda(\mu)$
RGE scale $\mu$ in GeV
0.06
0.04
0.02
0.00
−0.02
−0.04
−0.06
$10^2$ $10^4$ $10^6$ $10^8$ $10^{10}$ $10^{12}$ $10^{14}$ $10^{16}$ $10^{18}$ $10^{20}$

# Many open problems

Flavors and families, mass and mixings

Matter-antimatter asymmetry

What stabilises the SM?

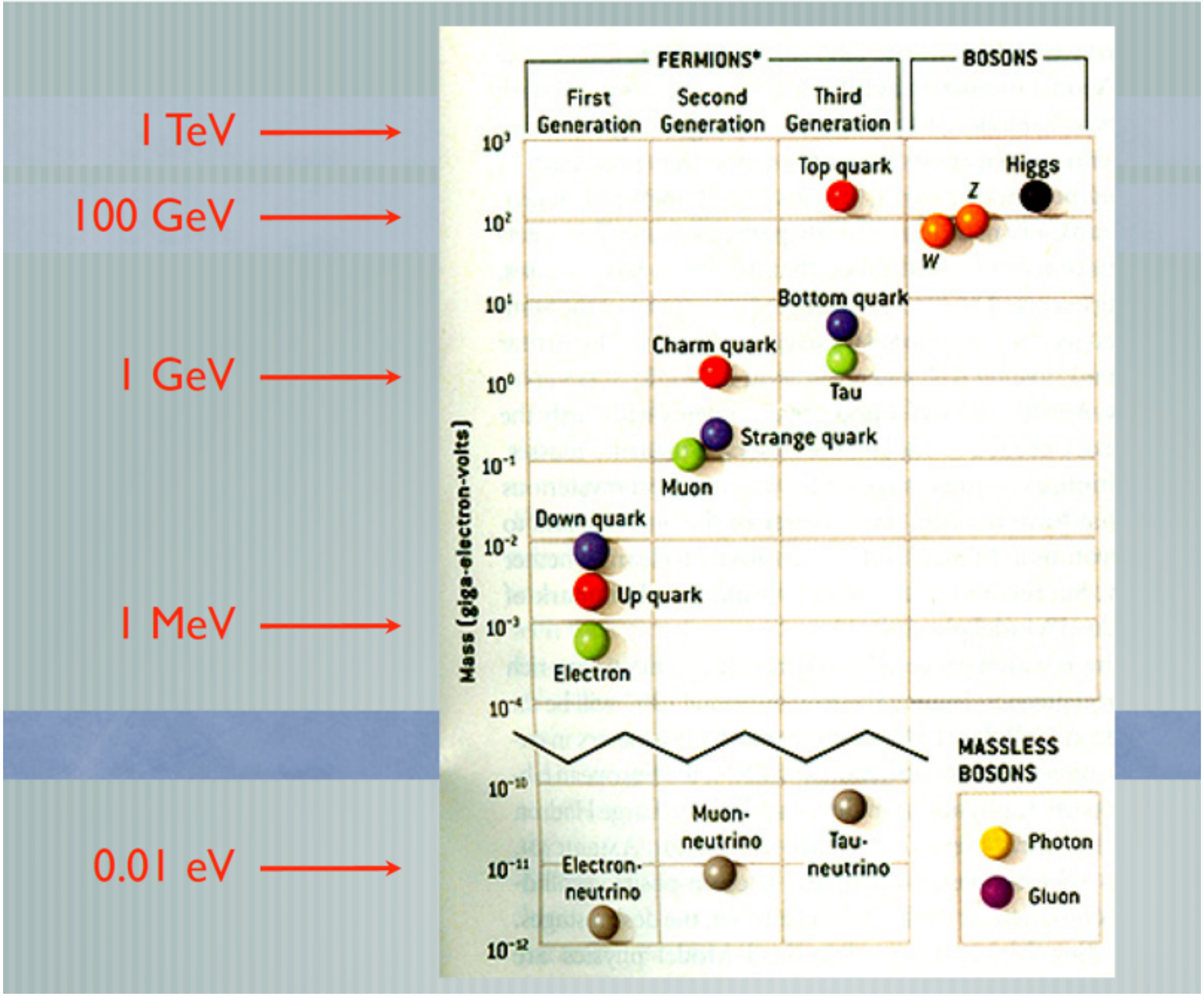
Neutrino oscillations masses and mixings

Baryogenesis, leptogenesis

Gravity?

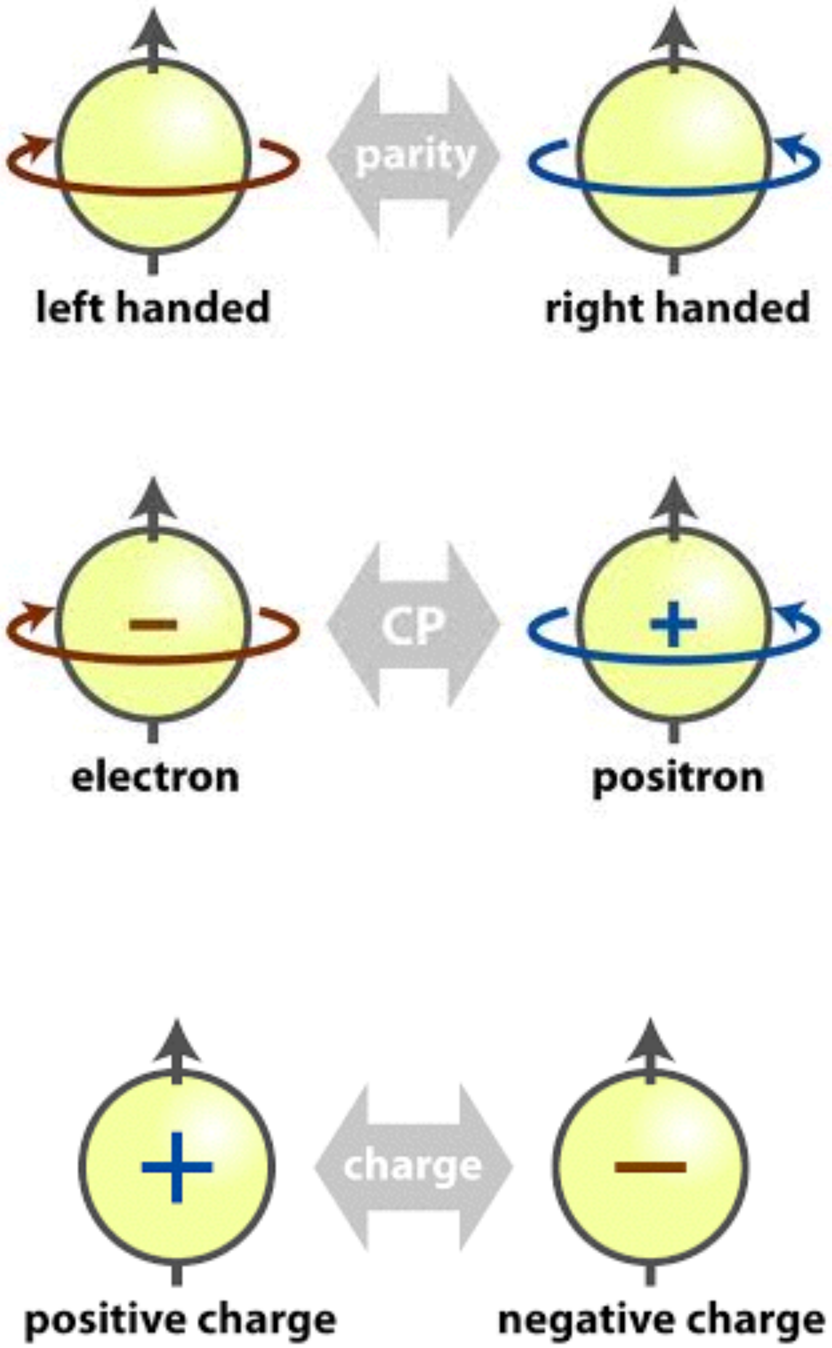
Black holes?

Dark matter and energy…



1 TeV
100 GeV
1 GeV
1 MeV
0.01 eV
FERMIONS*
First Generation
Second Generation
Third Generation
BOSONS
Mass (giga-electron-volts)
Top quark
Higgs
Z
W
Bottom quark
Charm quark
Tau
Strange quark
Muon
Down quark
Up quark
Electron
MASSLESS BOSONS
Muon-neutrino
Tau-neutrino
Electron-neutrino
Photon
Gluon

# Discrete symmetries




$P \qquad C \qquad T \qquad CP \qquad CPT$

Discrete
Continuous:
Kinematical: space-time transformations
Internal: global, local (change with space)

Quantum implamentation:

$$[Q_a, H] = 0, \qquad Q_a|0> = 0$$ Wigner-Weyl

$$[Q_a, H] = 0, \qquad Q_a|0> \neq 0$$ Nambu-Goldstone

Every broken symmetry has associated a massless particle
Examples of both types abound in CMP and PP. It is a quantum phenomenon in the SM. The Higgs particle does not give mass. It is the Higgs vacuum. It explains the masses of W,Z and accommodates the masses of the known quarks and leptons, but does not explain them.

The interplay between local (gauge) symmetries and SSB is the theme of this conference

Thank you