

INTERNATIONAL MASTERCLASSES

Hands on particle physics

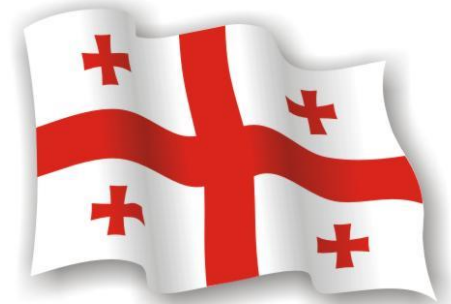
Fundamental Particles in the Standard Model

Gela Devidze

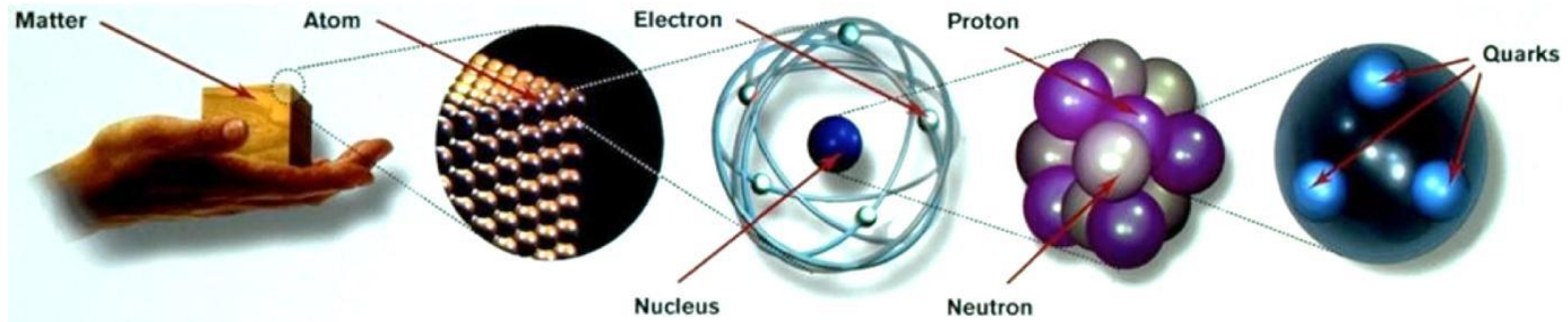
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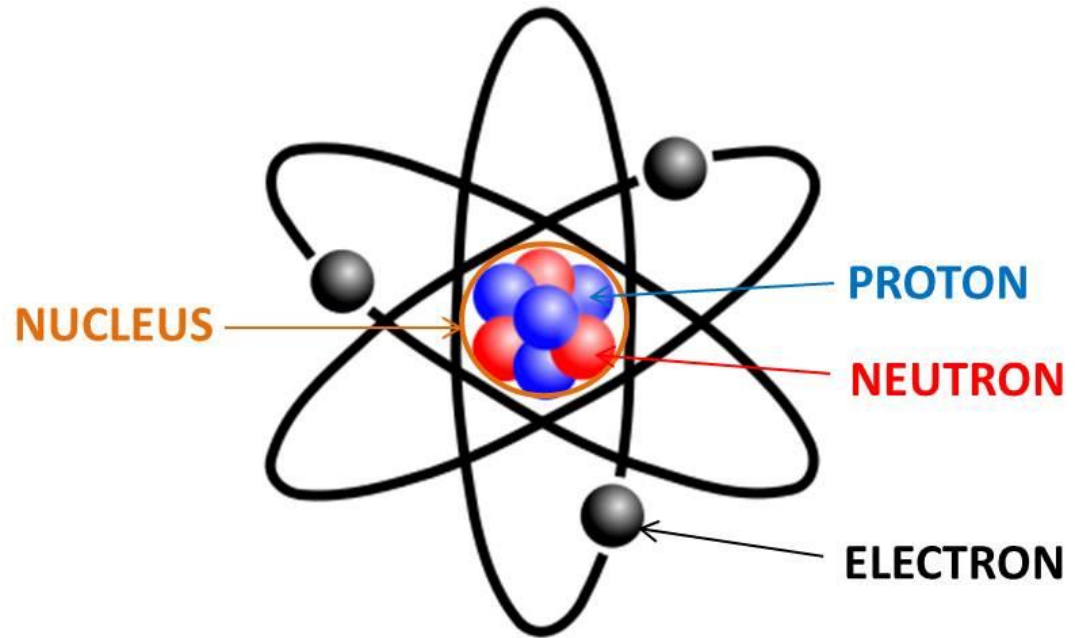


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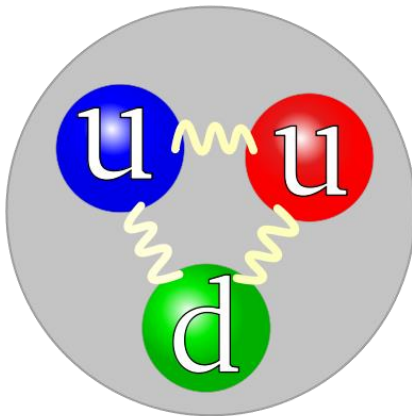


- **Atom**

- **Atom compositness.**
 - * **Neutrons.**
 - * **Protons.**
 - * **Electrons.**



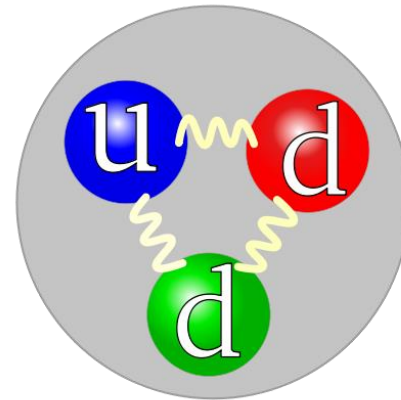
Proton



$$\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1$$

u u d

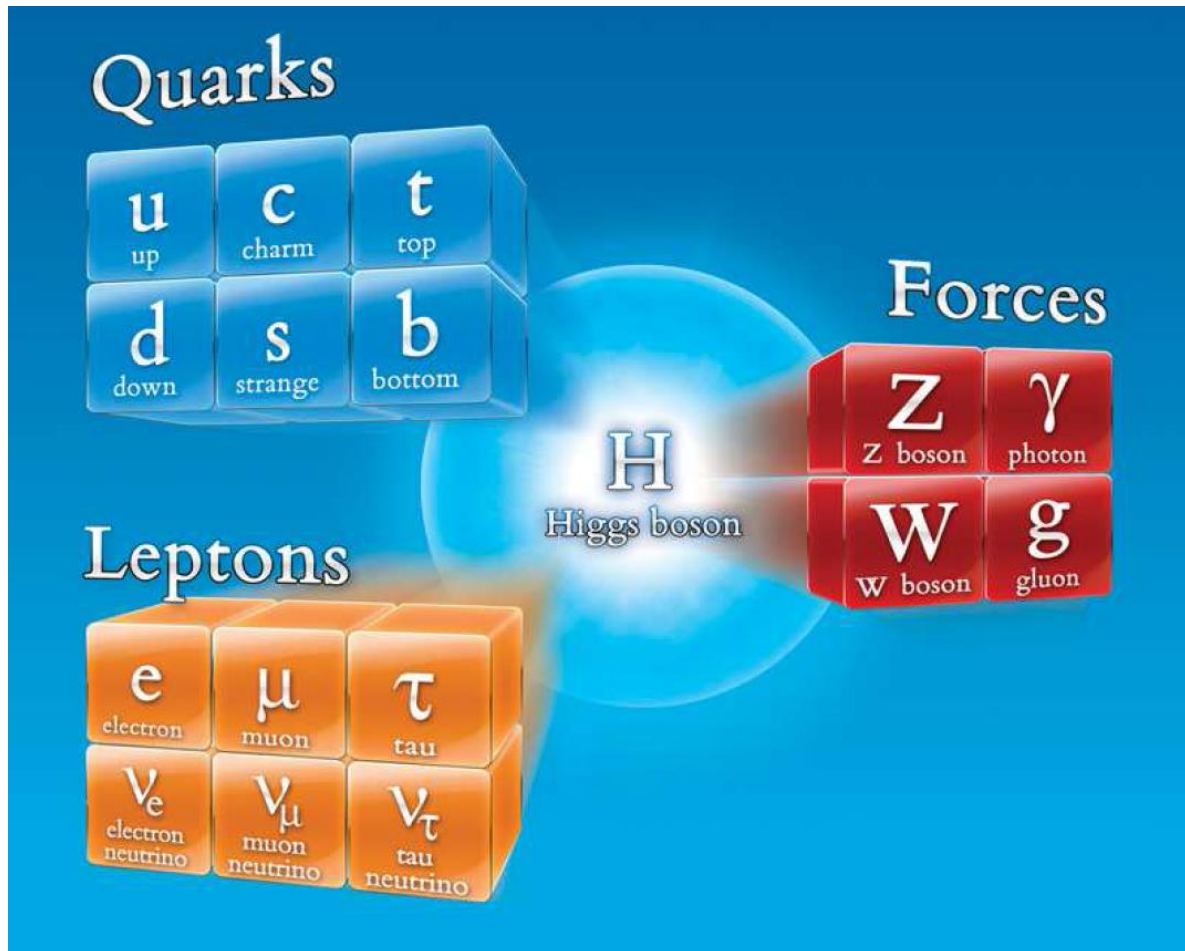
Neutron



$$\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$$

u d d

- **Proton and neutron compositeness.**
 - * Naively: up and down quarks.
 - * In reality: dynamical objects made of Valence and sea quarks. Gluons.



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სტანდარტულ მოდელში არსებული ფუნდამენტური ნაწილაკები

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

მატერიის ნაწილაკები :

კვარკები და ლეპტონები

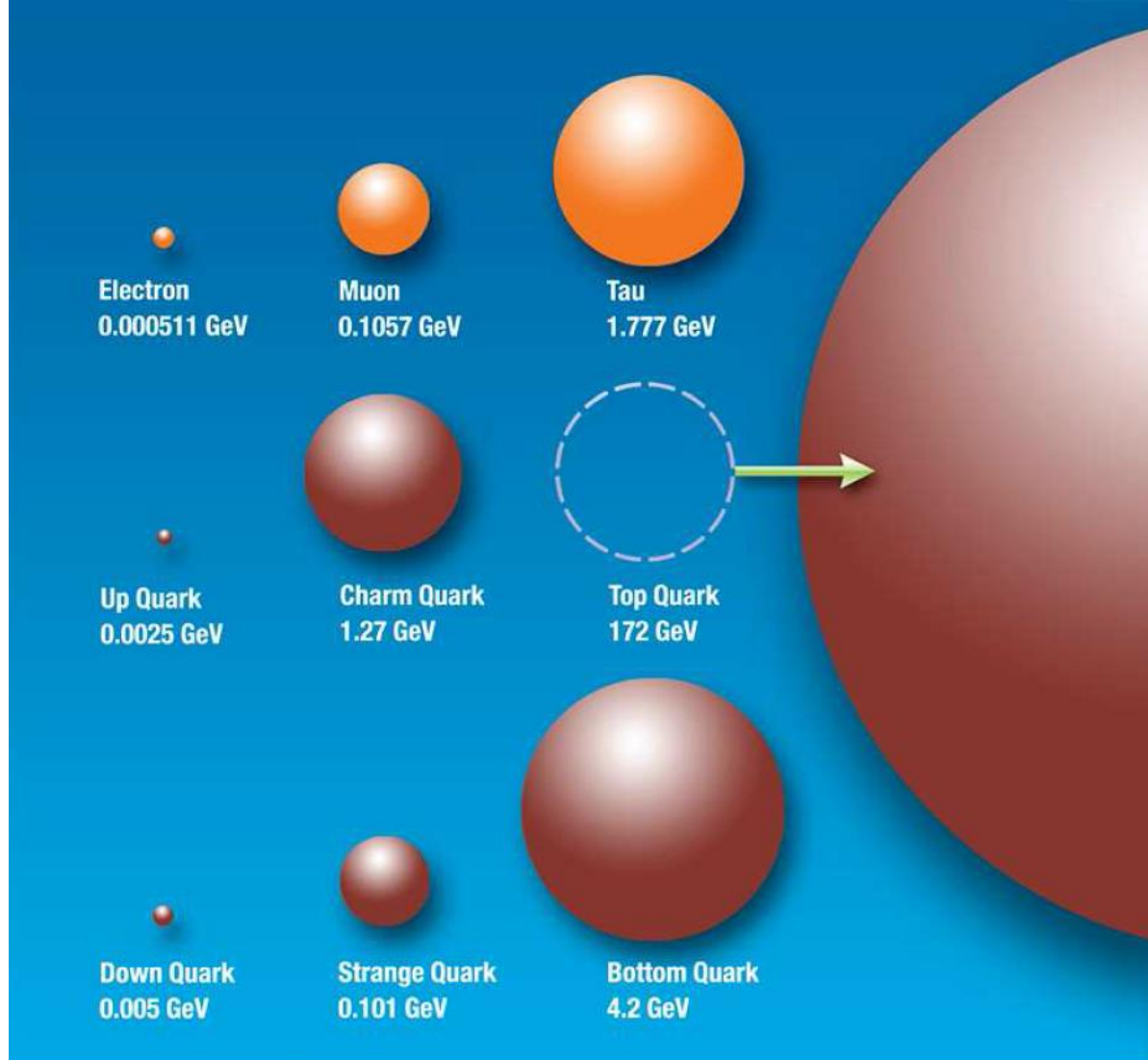
- ურთიერთქმედების გადამტანი ნაწილაკები:

ფოტონი

გლუონი

სუსტი ურთიერთქმედების გადამტანი ნეიტრალური და დამუხტული ბოზონები

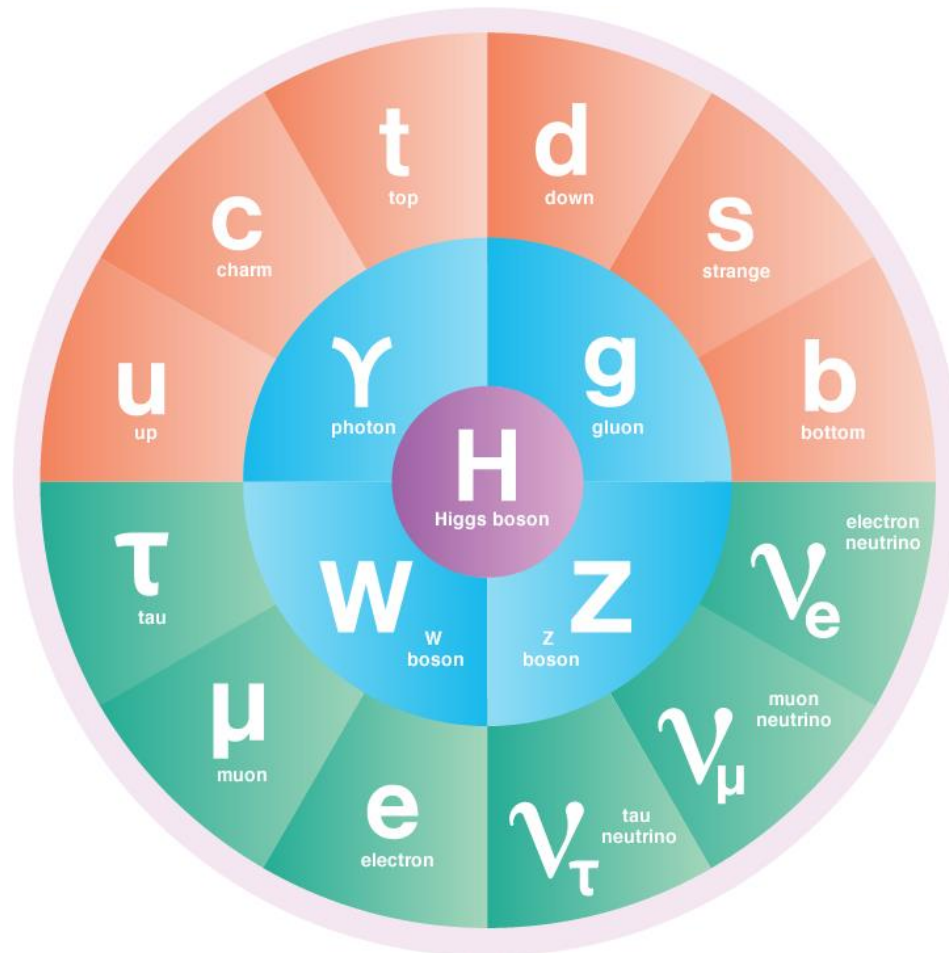
ჰიგსის ბოზონი



In addition, the associated antiparticles.

The only difference between generations lies in the (increasing) mass.

**Experimental status
[Particle Data Group
Review].**



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*** All these particules have been observed.**

*** Last ones: top quark (1995), tau neutrino (2000) and Higgs Boson (2012).**



Discovered in 2012, the Higgs boson was the last missing piece of the Standard Model puzzle. It is a different kind of force carrier from the other elementary forces, and it gives mass to quarks as well as the W and Z bosons. Whether it also gives mass to neutrinos remains to be discovered.

Mass: 125 GeV; Spin: 0; Discovered at CERN

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You can write(schematically) the Standard Model Lagrangian on your T-short



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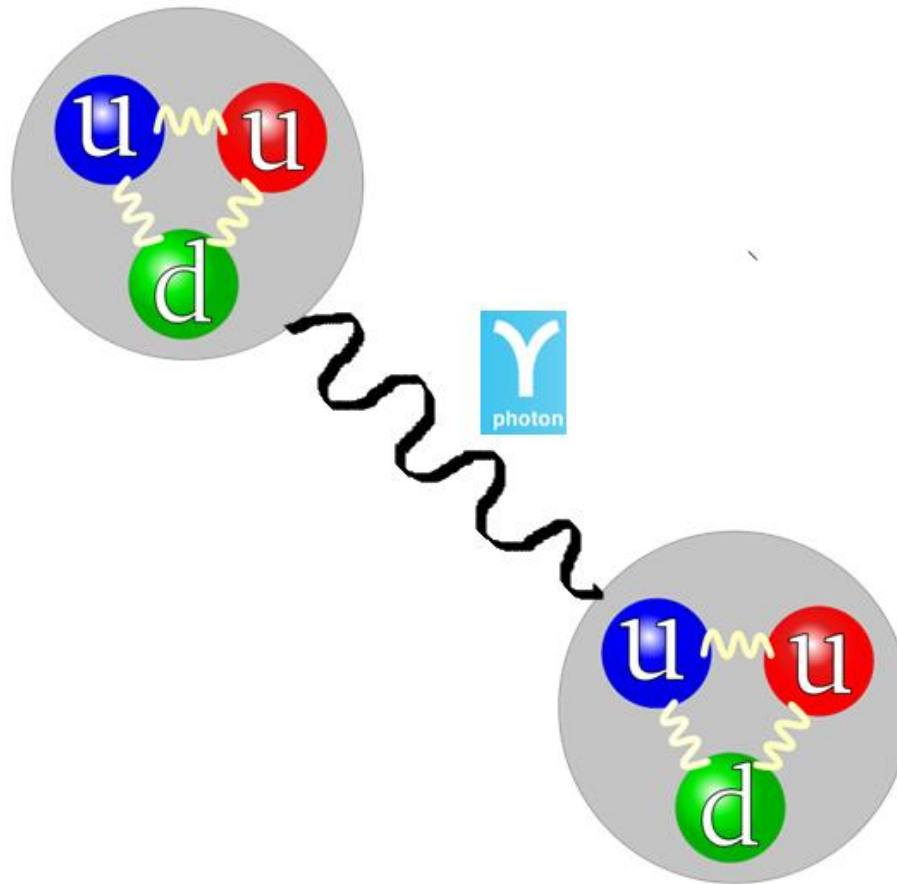
The Standard Model Lagranjian in detail

$$\begin{aligned}
\mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
& M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \frac{1}{2c_w^2} M^2 Z_\mu^0 Z_\mu^0 - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - i g c_w (\partial_\nu Z_\mu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - Z_\nu^0 (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + Z_\mu^0 (W_\nu^+ \partial_\mu W_\nu^- - W_\nu^- \partial_\mu W_\nu^+)) - \\
& i g s_w (\partial_\nu A_\mu (W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu (W_\mu^+ \partial_\nu W_\mu^- - W_\mu^- \partial_\nu W_\mu^+) + A_\mu (W_\nu^+ \partial_\mu W_\nu^- - \\
& W_\nu^- \partial_\mu W_\nu^+)) - \frac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - \\
& Z_\mu^0 Z_\nu^0 W_\mu^+ W_\nu^-) + g^2 s_w^2 (A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\nu W_\mu^+ W_\nu^-) + g^2 s_w c_w (A_\mu Z_\nu^0 (W_\mu^+ W_\nu^- - \\
& W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-) - \frac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
& \beta_h \left(\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-) \right) + \frac{2M^4}{g^2} \alpha_h - \\
& g \alpha_h M (H^3 + H \phi^0 \phi^0 + 2H \phi^+ \phi^-) - \\
& \frac{1}{8}g^2 \alpha_h (H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2) - \\
& g M W_\mu^+ W_\mu^- H - \frac{1}{2}g \frac{M}{c_w^2} Z_\mu^0 Z_\mu^0 H - \\
& \frac{1}{2}ig (W_\mu^+ (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W_\mu^- (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)) + \\
& \frac{1}{2}ig (W_\mu^+ (H \partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}ig \frac{1}{c_w} (Z_\mu^0 (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
& M (\frac{1}{c_w} Z_\mu^0 \partial_\mu \phi^0 + W_\mu^+ \partial_\mu \phi^- + W_\mu^- \partial_\mu \phi^+) - i g \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + i g s_w M A_\mu (W_\mu^+ \phi^- - \\
& W_\mu^- \phi^+) - i g \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
& \frac{1}{4}g^2 W_\mu^+ W_\mu^- (H^2 + (\phi^0)^2 + 2\phi^+ \phi^-) - \frac{1}{8}g^2 \frac{1}{c_w^2} Z_\mu^0 Z_\mu^0 (H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+ \phi^-) - \\
& \frac{1}{2}g^2 \frac{s_w^2}{c_w} Z_\mu^0 \phi^0 (W_\mu^+ \phi^- + W_\mu^- \phi^+) - \frac{1}{2}ig^2 \frac{s_w^2}{c_w} Z_\mu^0 H (W_\mu^+ \phi^- - W_\mu^- \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0 (W_\mu^+ \phi^- + \\
& W_\mu^- \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H (W_\mu^+ \phi^- - W_\mu^- \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z_\mu^0 A_\mu \phi^+ \phi^- - \\
& g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- + \frac{1}{2}ig_s \lambda_{ij}^a (\bar{q}_i^\sigma \gamma^\mu q_j^\sigma) g_\mu^a - \bar{e}^\lambda (\gamma^\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda (\gamma^\partial + m_\nu^\lambda) \nu^\lambda - \bar{u}_j^\lambda (\gamma^\partial + \\
& m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma^\partial + m_d^\lambda) d_j^\lambda + i g s_w A_\mu (-\bar{e}^\lambda \gamma^\mu e^\lambda) + \frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda) + \\
& \frac{ig}{4c_w} Z_\mu^0 \{ (\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\
& (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 + \gamma^5) u_j^\lambda) \} + \frac{ig}{2\sqrt{2}} W_\mu^+ ((\bar{\nu}^\lambda \gamma^\mu (1 + \gamma^5) U^{lep}_{\lambda\kappa} e^\kappa) + (\bar{u}_j^\lambda \gamma^\mu (1 + \gamma^5) C_{\lambda\kappa} d_j^\kappa)) + \\
& \frac{ig}{2\sqrt{2}} W_\mu^- ((\bar{e}^\kappa U^{lep\dagger}_{\kappa\lambda} \gamma^\mu (1 + \gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C_{\kappa\lambda}^\dagger \gamma^\mu (1 + \gamma^5) u_j^\lambda)) + \\
& \frac{ig}{2M\sqrt{2}} \phi^+ (-m_e^\kappa (\bar{\nu}^\lambda U^{lep}_{\lambda\kappa} (1 - \gamma^5) e^\kappa) + m_\nu^\lambda (\bar{\nu}^\lambda U^{lep}_{\lambda\kappa} (1 + \gamma^5) e^\kappa) + \\
& \frac{ig}{2M\sqrt{2}} \phi^- (m_e^\lambda (\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa} (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep\dagger}_{\lambda\kappa} (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{m_\nu^\lambda}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
& \frac{g}{2} \frac{m_\nu^\lambda}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\nu^2}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa} (1 - \gamma_5) \hat{\nu}_\kappa - \\
& \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (1 - \gamma_5) \hat{\nu}_\kappa + \frac{ig}{2M\sqrt{2}} \phi^+ (-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1 - \gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1 + \gamma^5) d_j^\kappa) + \\
& \frac{ig}{2M\sqrt{2}} \phi^- (m_d^\lambda (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 + \gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger (1 - \gamma^5) u_j^\kappa) - \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
& \frac{g}{2} \frac{m_\lambda^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g_\mu^c + \\
& \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + i g c_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
& \partial_\mu \bar{X}^+ X^0) + i g s_w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + i g c_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
& \partial_\mu \bar{X}^0 X^+) + i g s_w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) + i g s_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
& \partial_\mu \bar{X}^- X^-) - \frac{1}{2}g M (\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c_w} \bar{X}^0 X^0 H) + \frac{1-2c_w^2}{2c_w} i g M (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
& \frac{1}{2c_w} i g M (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + i g M s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
& \frac{1}{2} i g M (\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0) .
\end{aligned}$$

- **Electromagnetism.**
 - * Interactions between charged particles (quarks and charged leptons).
 - * Mediated by massless photons (spin one).
- **Weak interaction.**
 - * Interactions between the left-handed components of the fermions.
 - * Mediated by massive weak bosons W and Z (spin one).
 - * Self interactions between W and Z bosons (and photons) [see below...].
- **Strong interactions.**
 - * Interactions between colored particles (quarks).
 - * Mediated by massless gluons g (spin one).
 - * Self interactions between gluons.
 - * Hadrons and mesons are made of quarks and gluons.
 - * At the nucleus level: binding of protons and neutrons.
- **Gravity.**
 - * Interactions between all particles.
 - * Mediated by the (non-observed) massless graviton (spin two).
 - * Not described by the Standard Model.
 - * Attempts: superstrings, M-theory, quantum loop gravity, ...

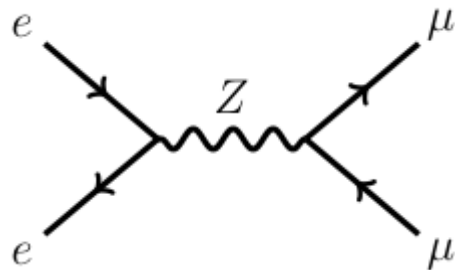
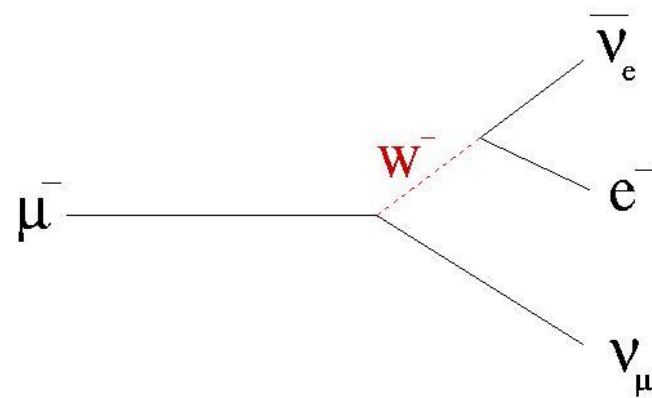
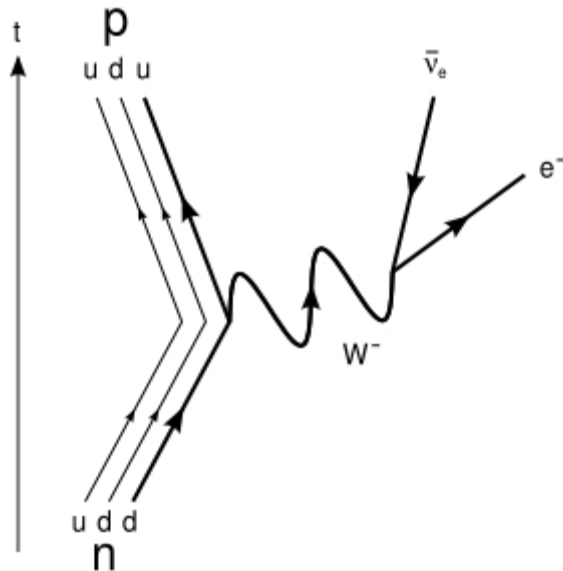
Electromagnetism.

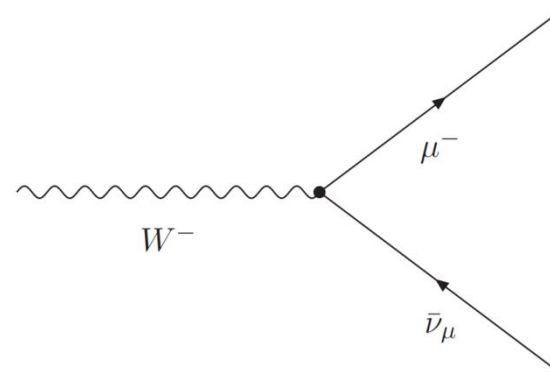
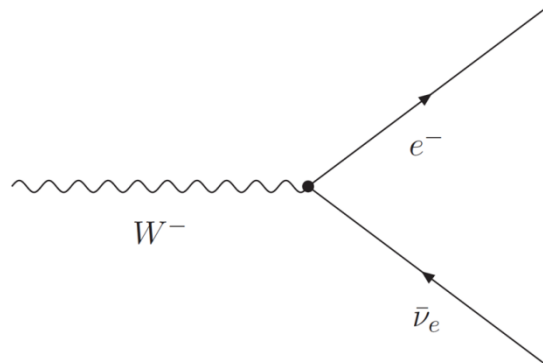
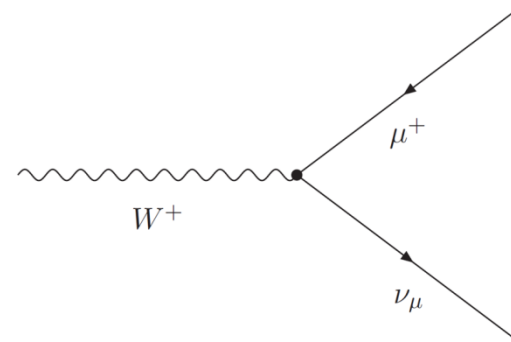
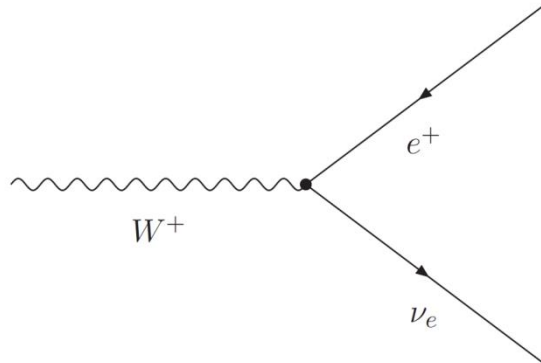
- * Interactions between charged particles (quarks and charged leptons).
- * Mediated by massless photons (spin one).



Weak interaction.

- * Interactions between the left-handed components of the fermions.
- * Mediated by massive weak bosons W and Z .
- * Self interactions between W and Z bosons

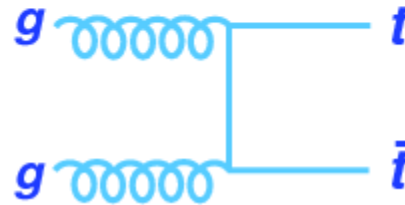


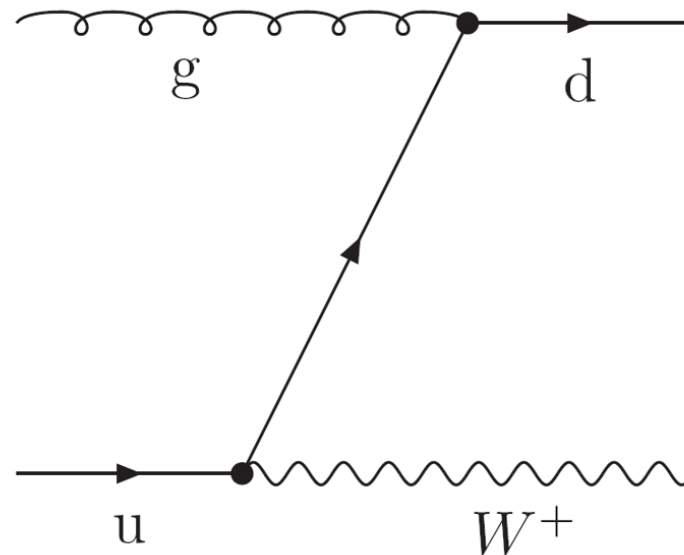
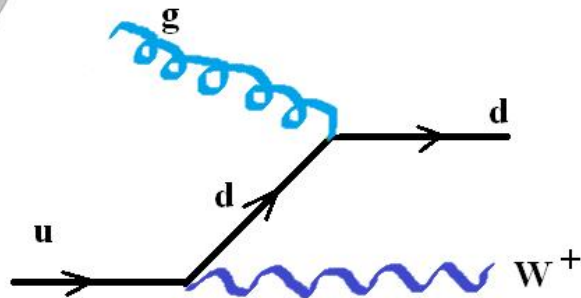
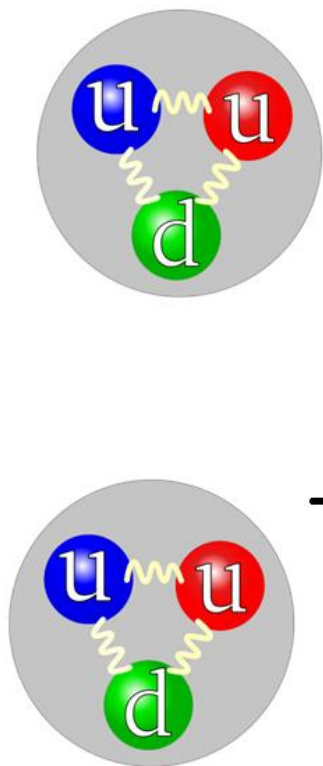


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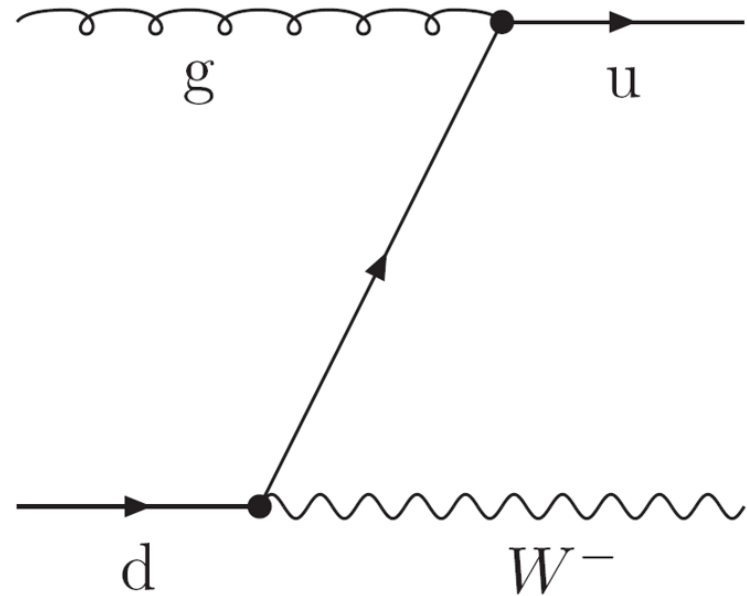
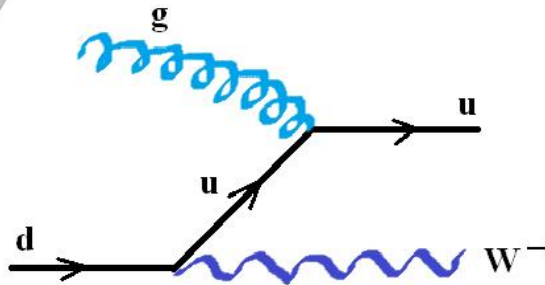
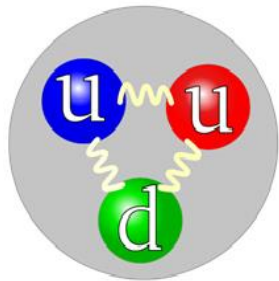
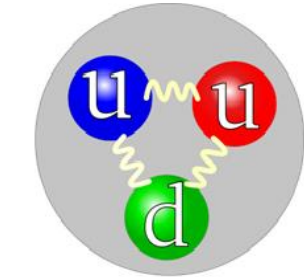
Strong interactions.

- * Interactions between colored particles (quarks).
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- * Self interactions between gluons.
- * Hadrons and mesons are made of quarks and gluons.
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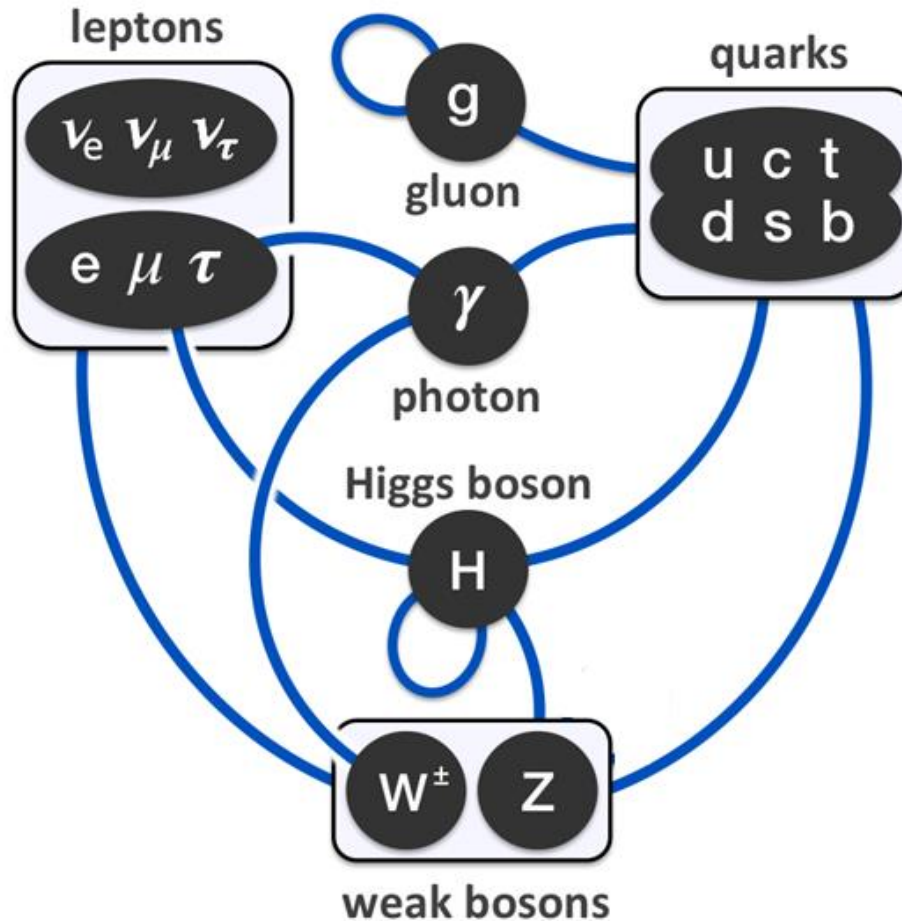


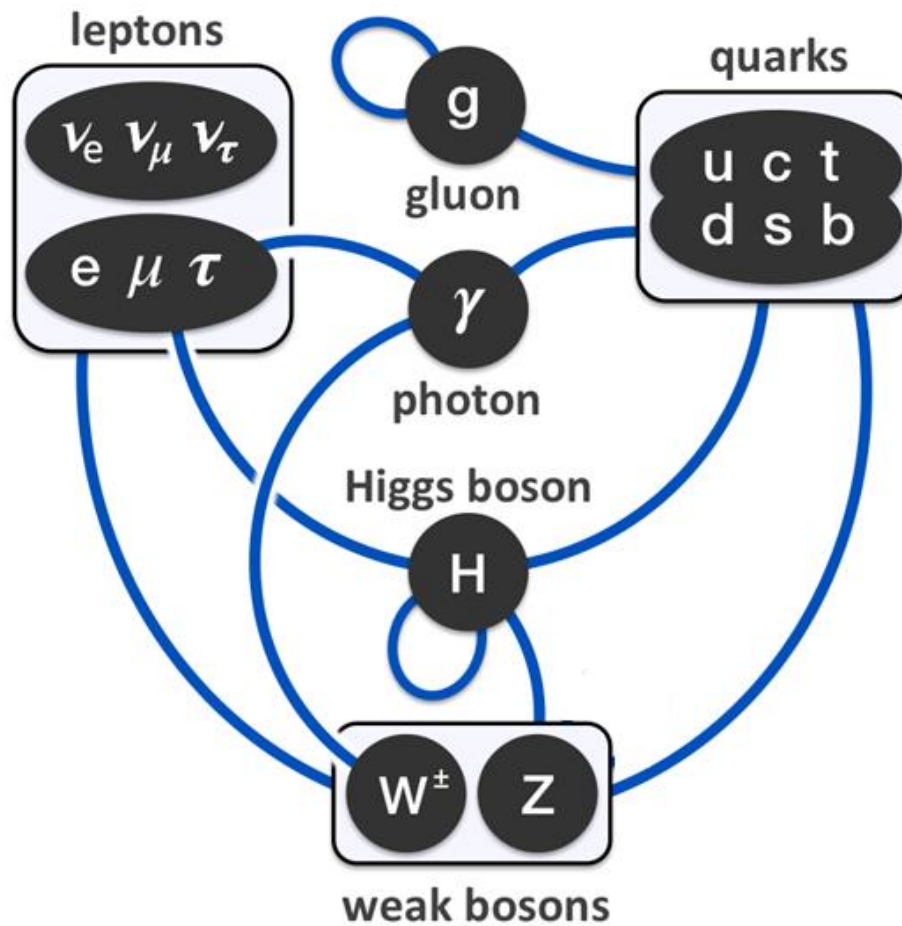
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სურათი ნაჩვენებია სქემატურად სტანდარტული მოდელის ნაწილაკების ურთიერთქმედება.

კვარკები მონაწილეობენ ელექტრომაგნიტურ, ძლიერ და სუსტ ურთიერთქმედებებში,
დამუხტული ლეპტონები - ელექტრომაგნიტურ და სუსტ ურთიერთქმედებებში,
ნეიტრინო - სუსტ ურთიერთქმედებაში.





	u up	c charm	t top
Mass	2.3 MeV	1.275 GeV	172 GeV
Charge	2/3	2/3	2/3
Spin	1/2	1/2	1/2
Discovered	1968 SLAC	1997 Brookhaven & SLAC	1995 Fermilab

	d down	s strange	b bottom
Mass	4.8 MeV	95 MeV	172 GeV
Charge	-1/3	-1/3	-1/3
Spin	1/2	1/2	1/2
Discovered	1968 SLAC	1947(1964) Manchester University	1977 Fermilab

	e electron	μ muon	τ tau
Mass	0.511 MeV	105.66 MeV	1776.82 MeV
Charge	-1	-1	-1
Spin	1/2	1/2	1/2
Discovered	1897 Cavendish Laboratory	1937 Caltech & Harvard	1976 SLAC

	ν_e	ν_μ	ν_τ
Mass	<2 eV	<0.19 MeV	<18.2 MeV
Charge	0	0	0
Spin	1/2	1/2	1/2
Discovered	1956 Savannah River Plant	1962 Brookhaven	2000 Fermilab

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PHOTON

**Discovered in:**

1923

Mass:

$<1 \times 10^{-18}$ eV

Discovered at:

Washington University

Charge:

0

Spin:

1

About:

The photon is the only elementary particle visible to the human eye—but only if it has the right energy and frequency (color). It transmits the electromagnetic force between charged particles.

W BOSON



Discovered in:

1983

Mass:

80.385 GeV

Discovered at:

CERN

Charge:

± 1

Spin:

1

About:

The W boson is the only force carrier that has an electric charge. It's essential for weak nuclear reactions: Without it, the sun would not shine.

Z BOSON



Discovered in:

1983

Mass:

91.1876 GeV

Discovered at:

CERN

Charge:

0

Spin:

1

About:

The Z boson is the electrically neutral cousin of the W boson and a heavy relative of the photon. Together, these particles explain the electroweak force

GLUON



Discovered in:

1979

Mass:

0

Discovered at:

DESY

Charge:

0

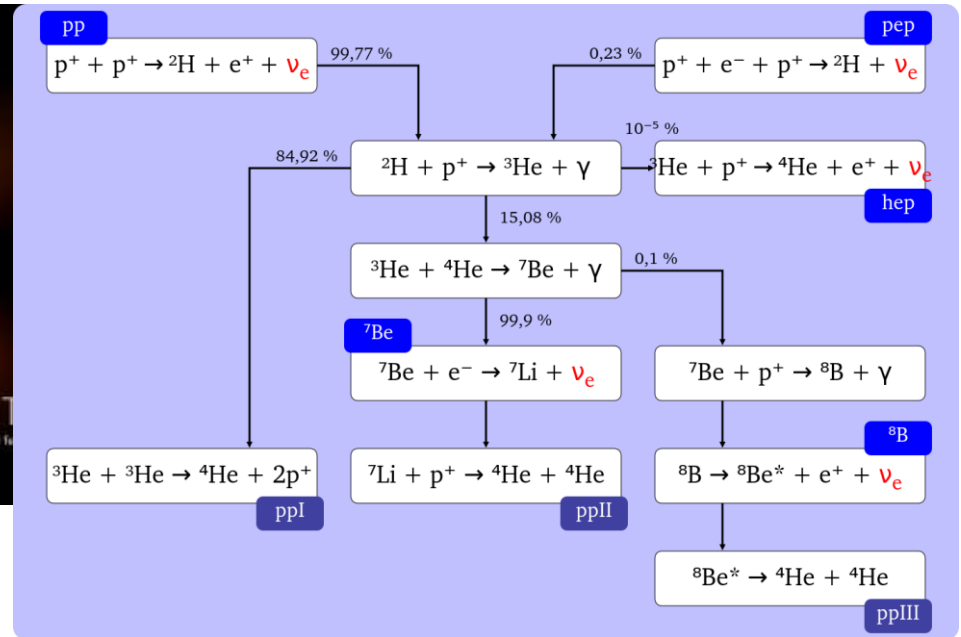
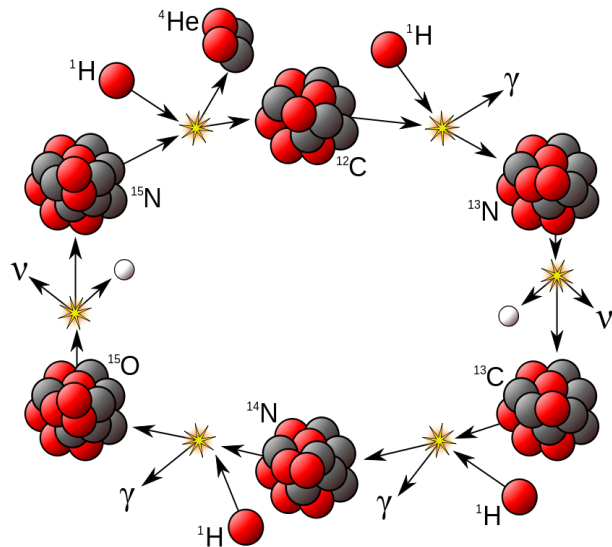
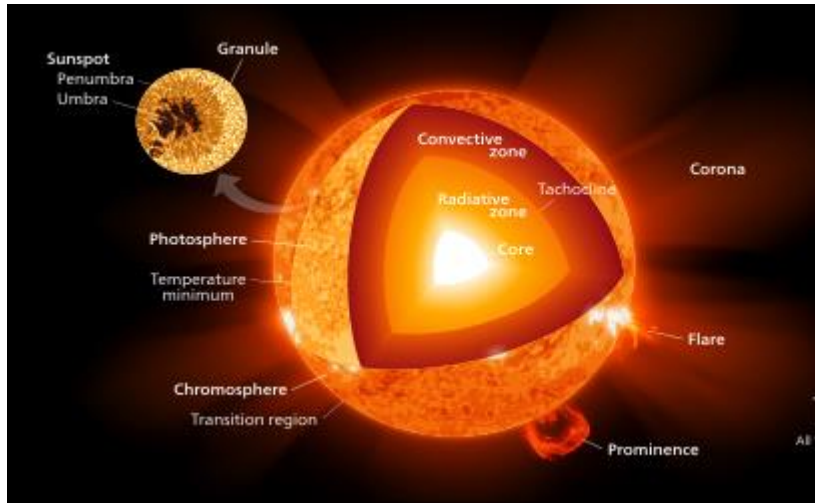
Spin:

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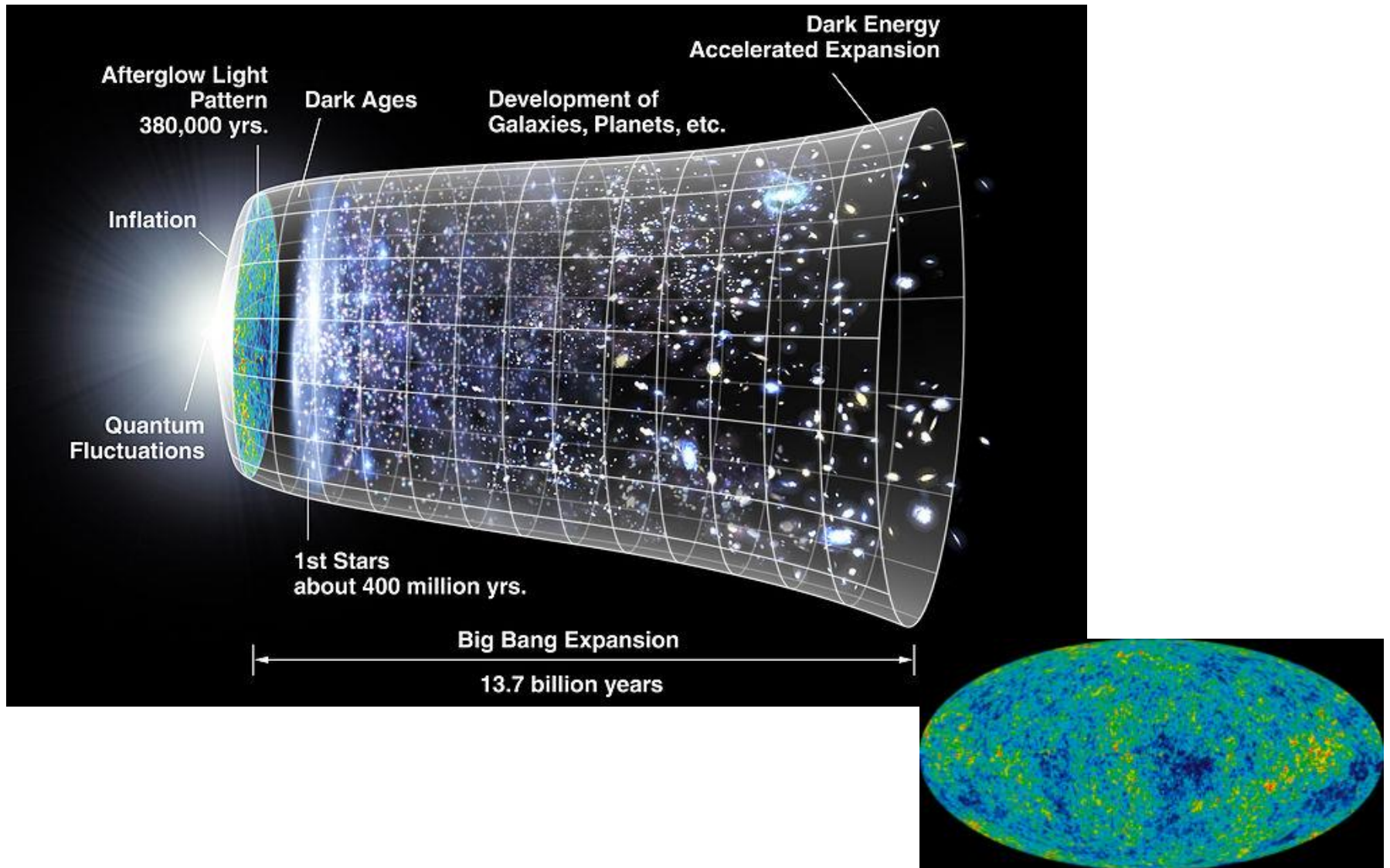
About:

The gluon is the glue that holds together quarks to form protons, neutrons and other particles. It mediates the strong nuclear force.

How the Sun shines



The Universe made selfie



TIMELINE OF THE INFLATIONARY UNIVERSE

Big Bang

In an infinitely dense moment 13.7 billion years ago, the Universe is born from a singularity.

Inflation

A mysterious particle or force accelerates the expansion. Some models inflate the Universe by a factor of 10^{26} in less than 10^{-32} seconds.

Cosmic microwave background

After 380,000 years, loose electrons cool enough to combine with protons. The Universe becomes transparent to light. The microwave background begins to shine.

Dark ages

Clouds of dark hydrogen gas cool and coalesce.

First stars

Gas clouds collapse. The fusion of stars begins.

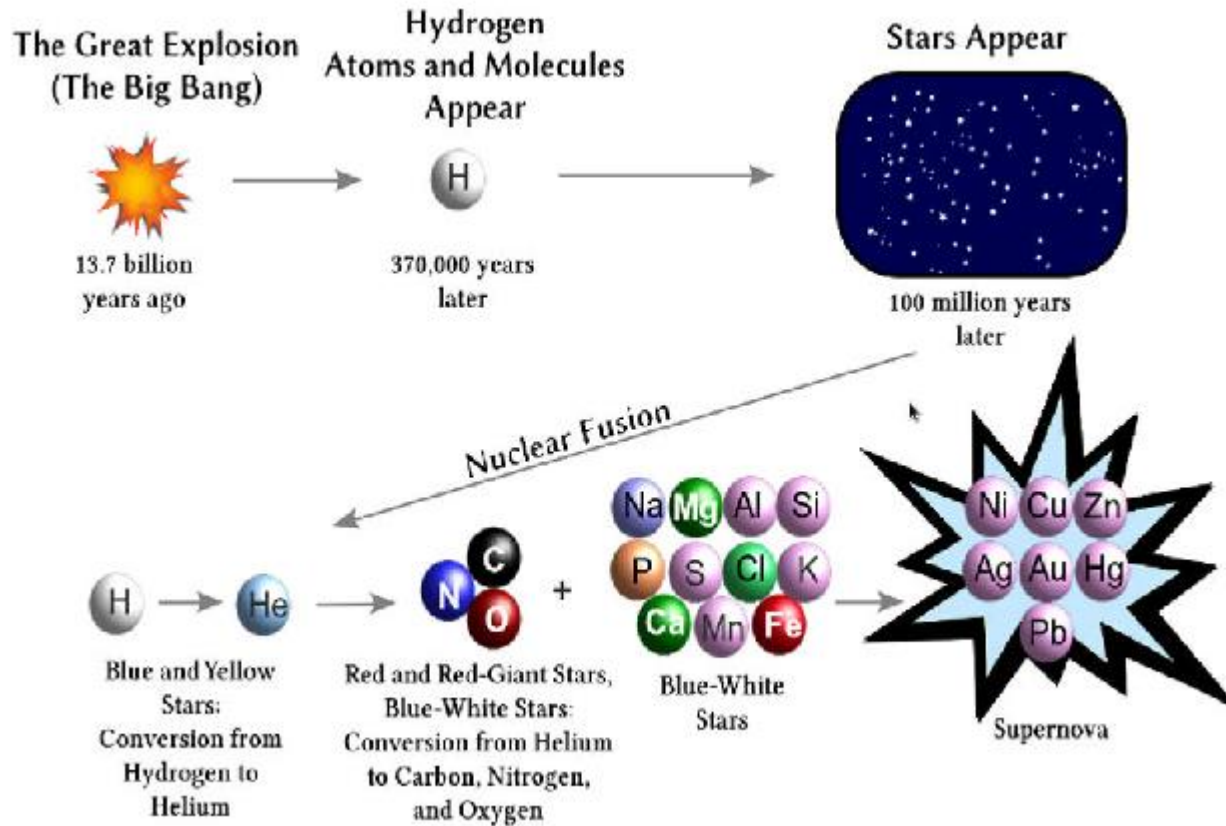
Galaxy formation

Gravity causes galaxies to form, merge and drift. Dark energy accelerates the expansion of the Universe, but at a much slower rate than inflation.

Big Bang expansion

13.7 billion years

INTERNATIONAL MASTERCLASSES - Hands on particle physics
March 26, 2019 Tbilisi, Georgia – Ivane Javakhishvili Tbilisi State University



All of you (me too) are made from fundamental particles (stars remnant) via fundamental interactions

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