

# INTERNATIONAL MASTERCLASSES

## Hands on particle physics

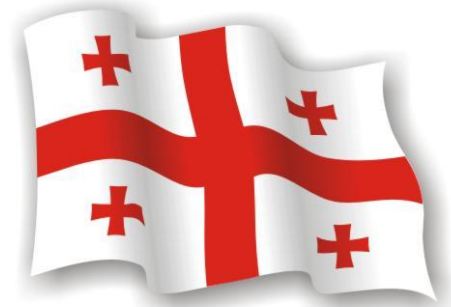
### Fundamental Particles in the Standard Model

*Gela Devidze*

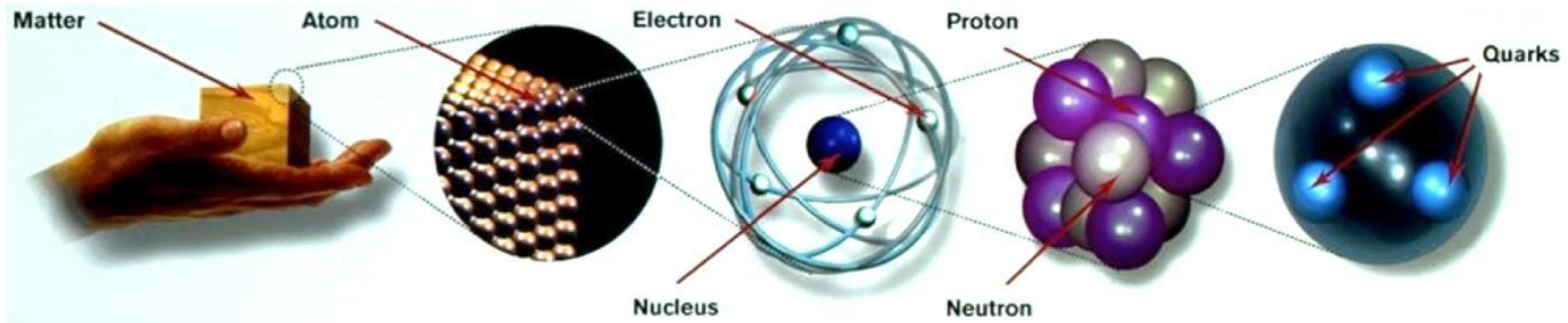
High Energy Physics Institute

Tbilisi State University

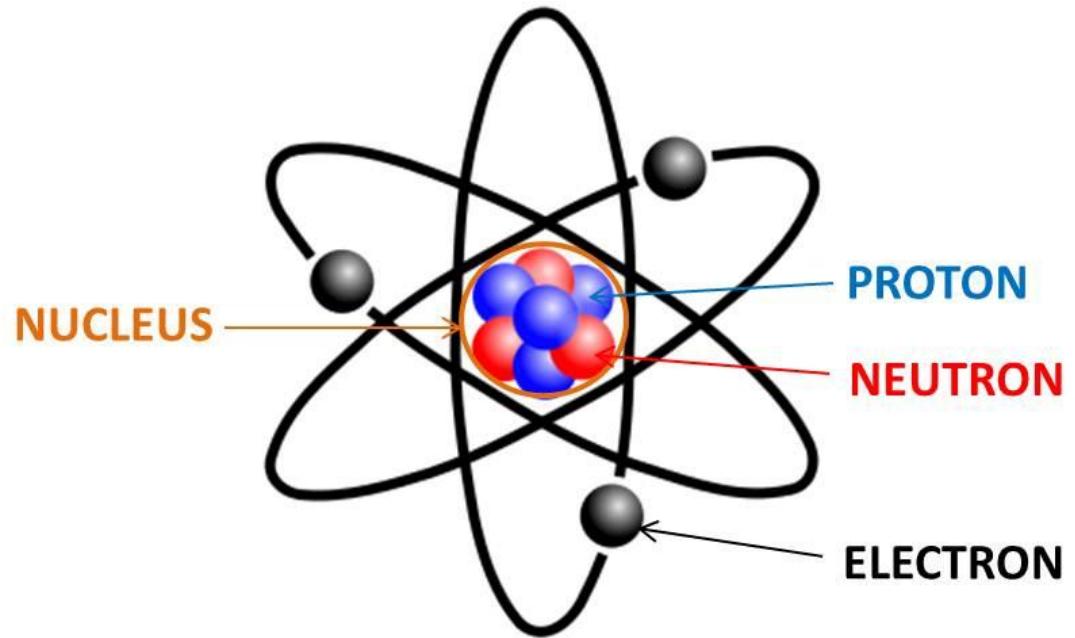
[gela.devidze@cern.ch](mailto:gela.devidze@cern.ch)



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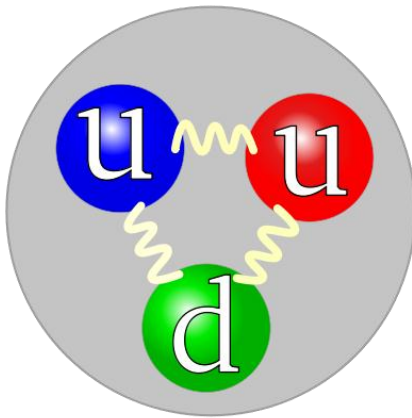


- **Atom**



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

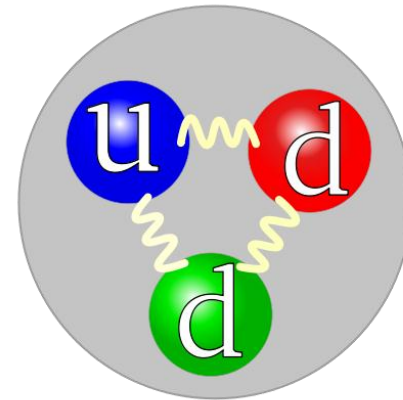
## Proton



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

u u d

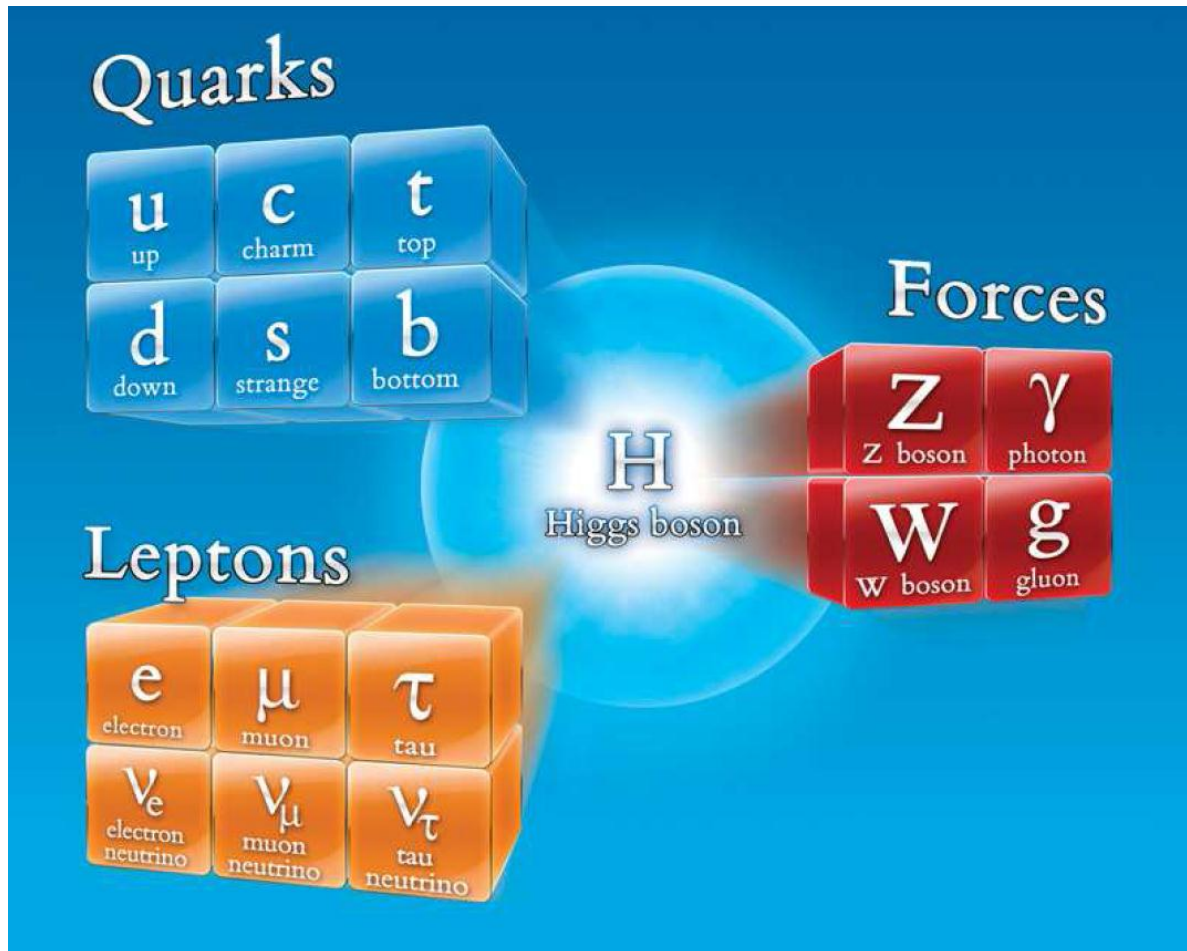
## Neutron



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

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
	<b>u</b> up	<b>c</b> charm	<b>t</b> top	<b><math>\gamma</math></b> photon	<b>H</b> Higgs boson
<b>QUARKS</b>					
	$\approx 4.8 \text{ MeV}/c^2$	$\approx 95 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0	
	-1/3	-1/3	-1/3	0	
	1/2	1/2	1/2	1	
	<b>d</b> down	<b>s</b> strange	<b>b</b> bottom	<b>g</b> gluon	
	$< 2.2 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 15.5 \text{ MeV}/c^2$	0	91.2 $\text{GeV}/c^2$
	0	0	0	0	1
	1/2	1/2	1/2	1	
	<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino	<b>Z</b> Z boson	
<b>LEPTONS</b>					<b>GAUGE BOSONS</b>
	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	$\pm 1$	
	1/2	1/2	1/2	1	
	<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau	<b>W</b> W boson	

მატერიის ნაწილაკები :

კვარკები და ლეპტონები

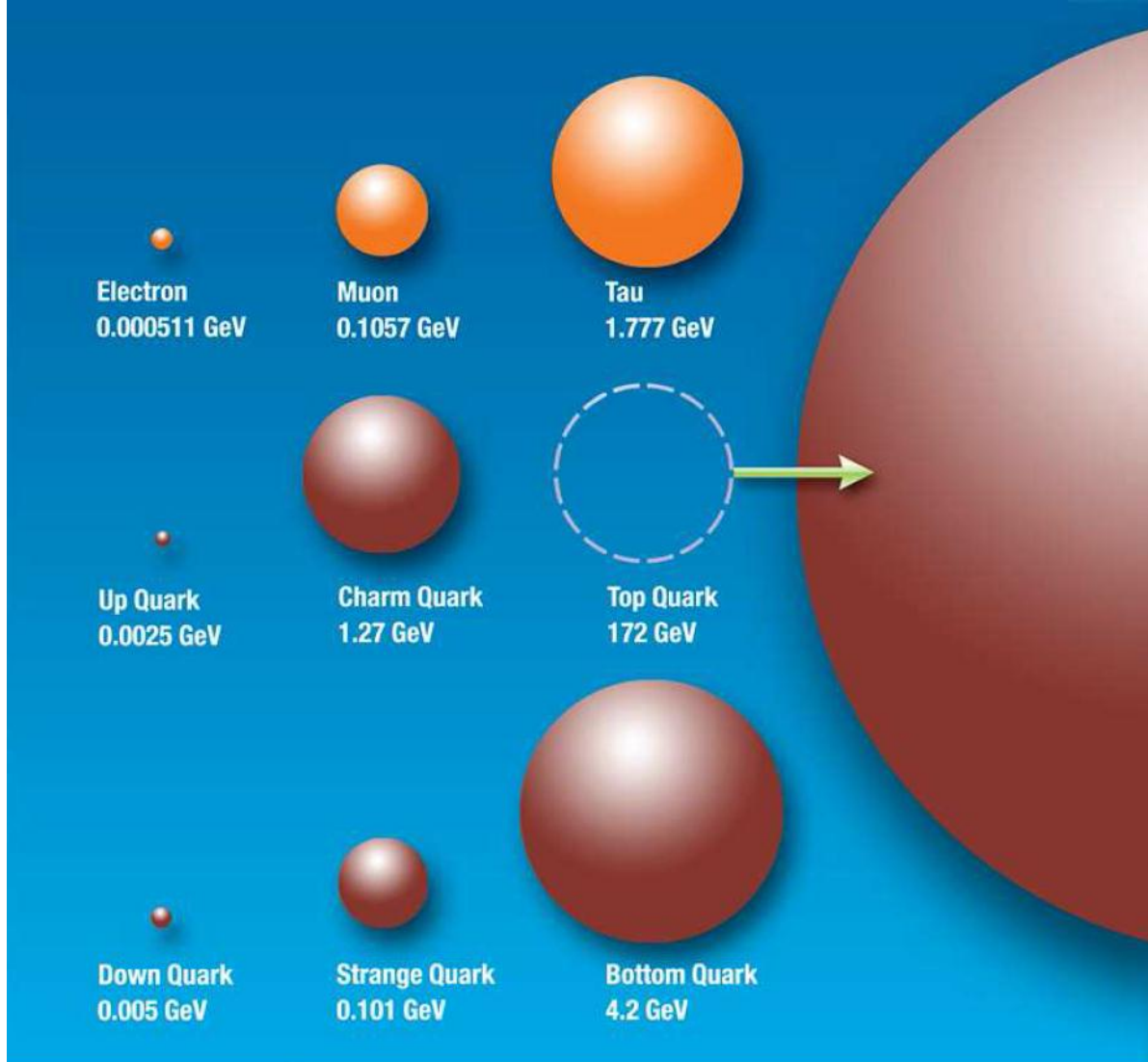
- ურთიერთქმედების გადამტანი ნაწილაკები:

ფოტონი

გლუონი

სუსტი ურთიერთქმედების გადამტანი ნეიტრალური და დამუხტული ბოზონები

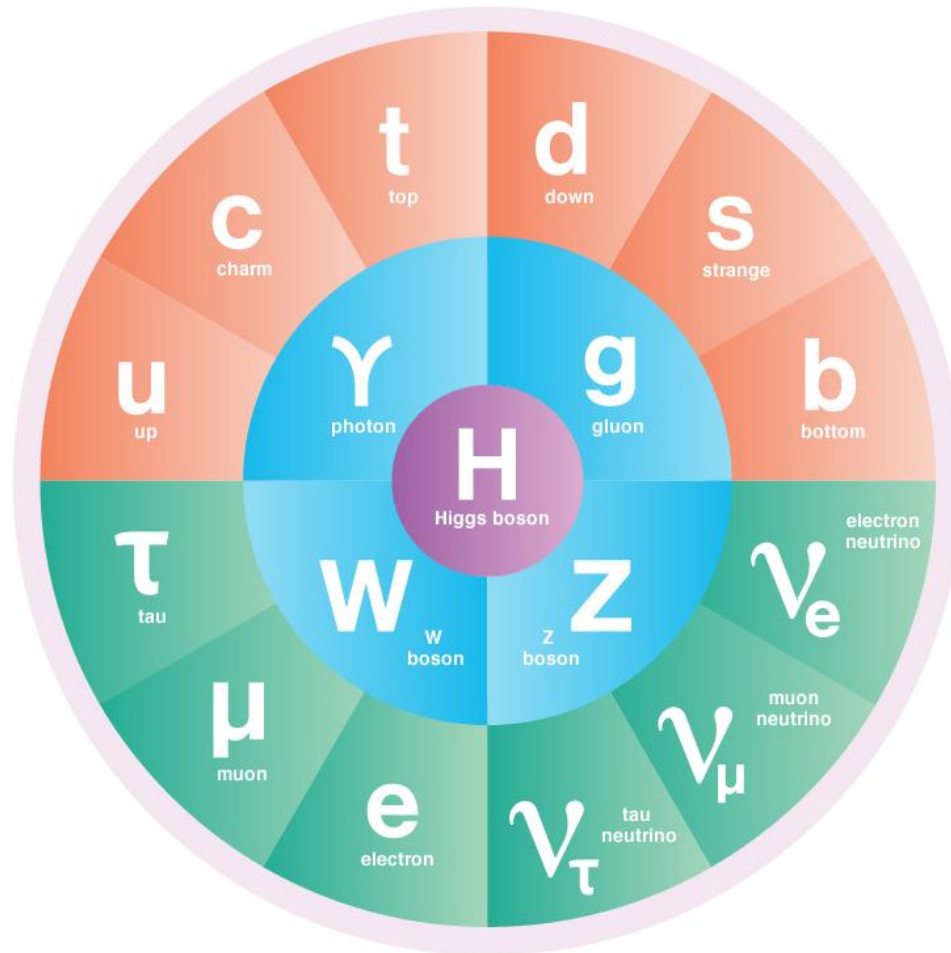
ჰიგსის ბოზონი



**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).**



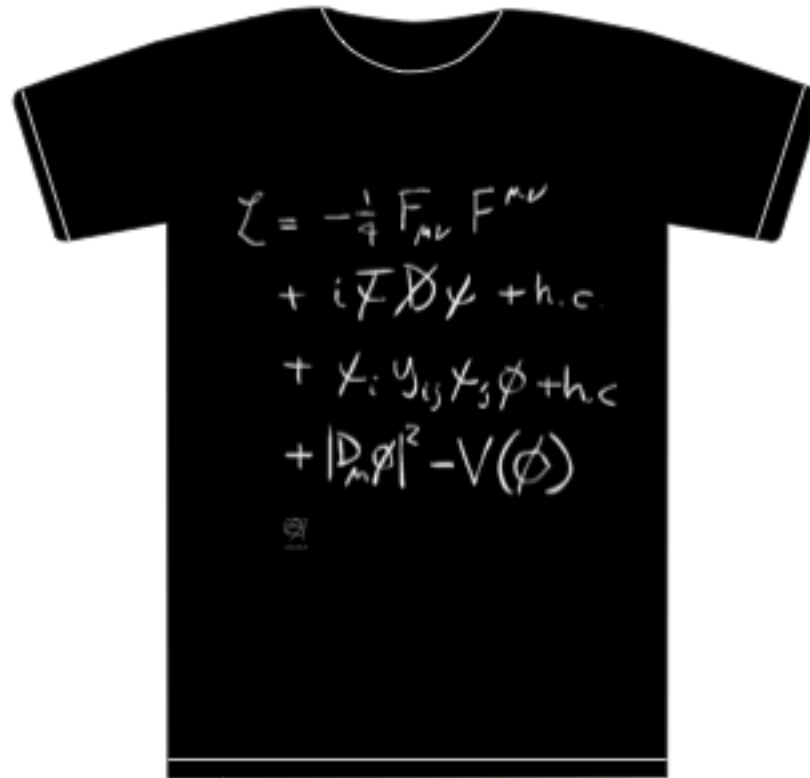
Discovered in 2012, the Higgs boson was the last missing piece of the Standard Model puzzle. It is a different kind of force carrier from the other elementary forces, and it gives mass to quarks as well as the W and Z bosons. Whether it also gives mass to neutrinos remains to be discovered.

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

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



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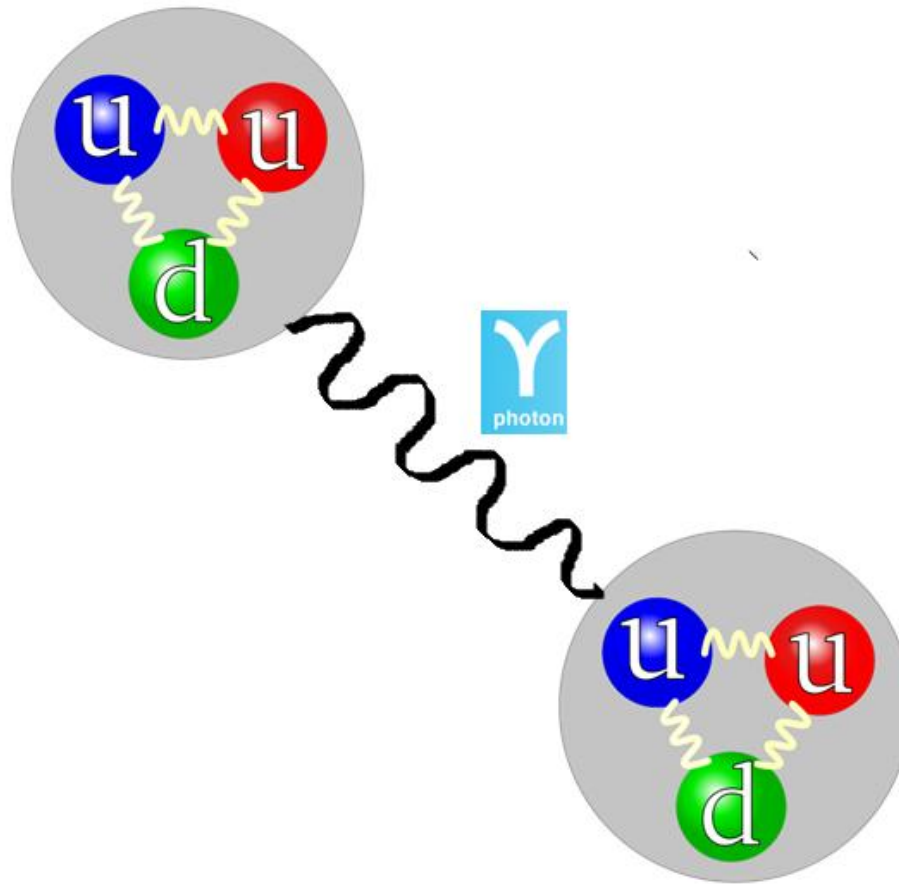
## The Standard Model Lagranjian in detail

$$\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 - igc_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_\mu^- - W_\nu^- \partial_\mu W_\mu^+) - \\
 & ig_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_\nu W_\mu^- - \\
 & W_\nu^- \partial_\nu W_\mu^+) - \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\nu^+ W_\mu^- + \frac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2 (Z_\mu^0 W_\nu^+ Z_\nu^0 W_\mu^- - \\
 & Z_\nu^0 Z_\mu^0 W_\nu^+ W_\mu^-) + g^2 s_w^2 (A_\mu W_\nu^+ A_\nu W_\mu^- - A_\mu A_\nu W_\nu^+ W_\mu^-) + 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) - \\
 & gM 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}g (W_\mu^+ (H\partial_\mu \phi^- - \phi^- \partial_\mu H) + W_\mu^- (H\partial_\mu \phi^+ - \phi^+ \partial_\mu H)) + \frac{1}{2}g \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^+)) - ig \frac{s_w^2}{c_w} M Z_\mu^0 (W_\mu^+ \phi^- - W_\mu^- \phi^+) + ig_s w M A_\mu (W_\mu^+ \phi^- - \\
 & W_\mu^- \phi^+) - ig \frac{1-2c_w^2}{2c_w} Z_\mu^0 (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + ig_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 + ig_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{1}{3}s_w^2 - 1 - \gamma^5) d_j^\lambda) + \\
 & (\bar{u}_j^\lambda \gamma^\mu (1 - \frac{2}{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}{}_{\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_d^\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}{}_{\lambda\kappa}^\dagger (1 + \gamma^5) \nu^\kappa) - m_\nu^\kappa (\bar{e}^\lambda U^{lep}{}_{\lambda\kappa}^\dagger (1 - \gamma^5) \nu^\kappa) - \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{e}^\lambda e^\lambda) + \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \frac{1}{4} \bar{\nu}_\lambda M_{\lambda\kappa}^R (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^2}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
 & \frac{g}{2} \frac{m_\lambda^2}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\lambda^2}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{C}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{C}^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 + igc_w W_\mu^+ (\partial_\mu \bar{X}^0 X^- - \\
 & \partial_\mu \bar{X}^+ X^0) + ig_s w W_\mu^+ (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W_\mu^- (\partial_\mu \bar{X}^- X^0 - \\
 & \partial_\mu \bar{X}^0 X^+) + ig_s w W_\mu^- (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z_\mu^0 (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) + ig_s w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
 & \partial_\mu \bar{X}^- X^-) - \frac{1}{2}gM (\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} igM (\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^-) + \\
 & \frac{1}{2c_w} igM (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + igM s_w (\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-) + \\
 & \frac{1}{2}igM (\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, ...

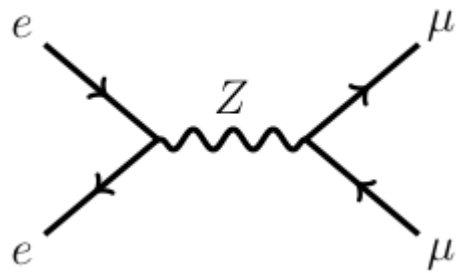
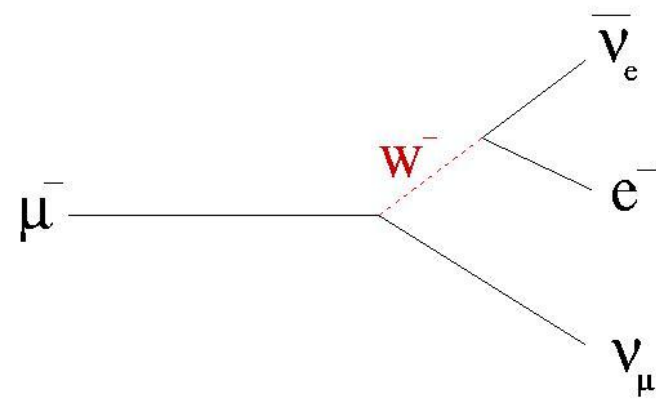
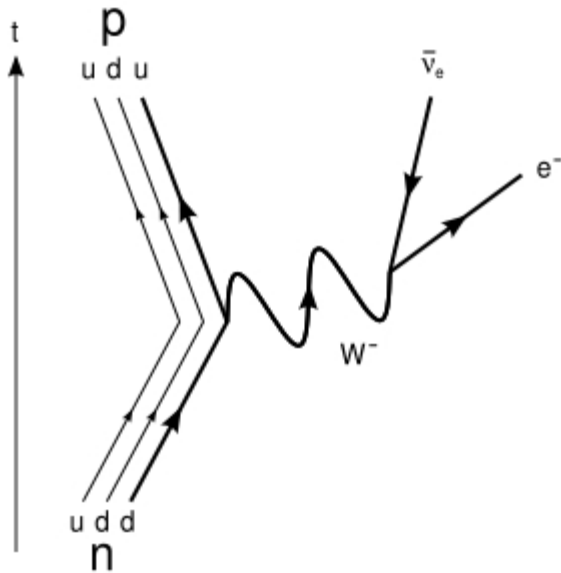
## Electromagnetism.

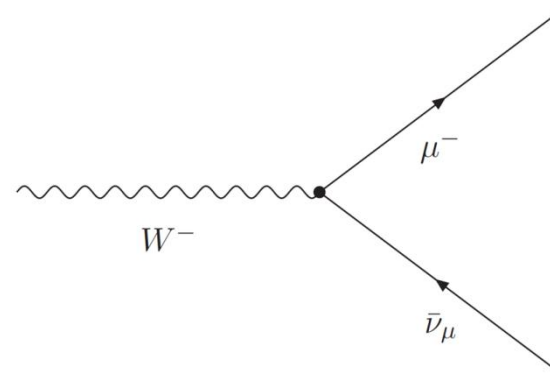
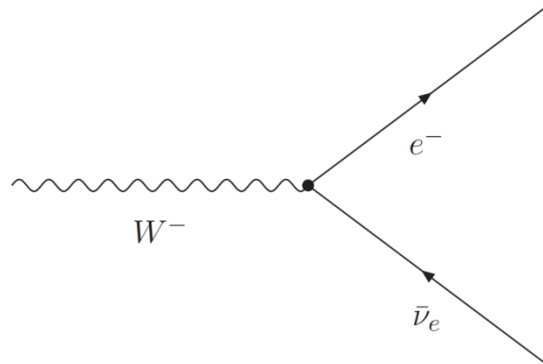
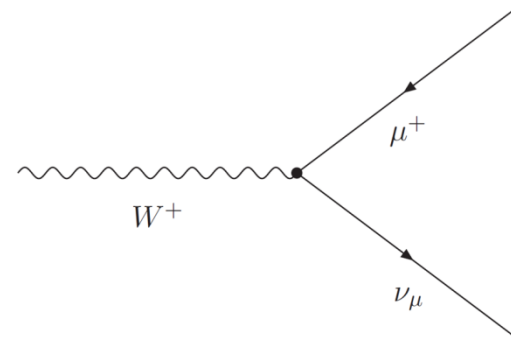
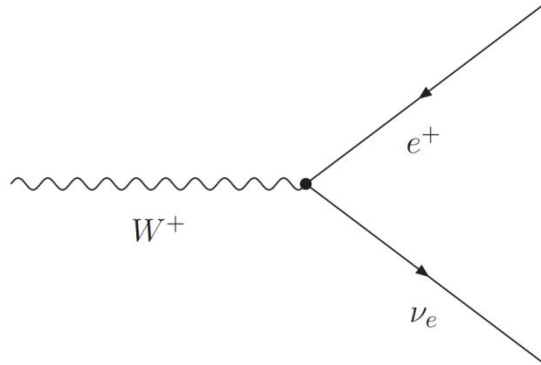
- \* Interactions between charged particles (quarks and charged leptons).
- \* Mediated by massless photons (spin one).



## 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

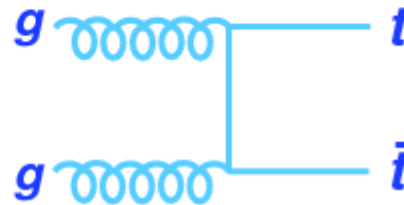
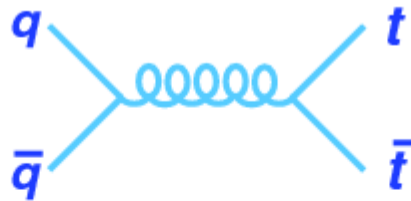


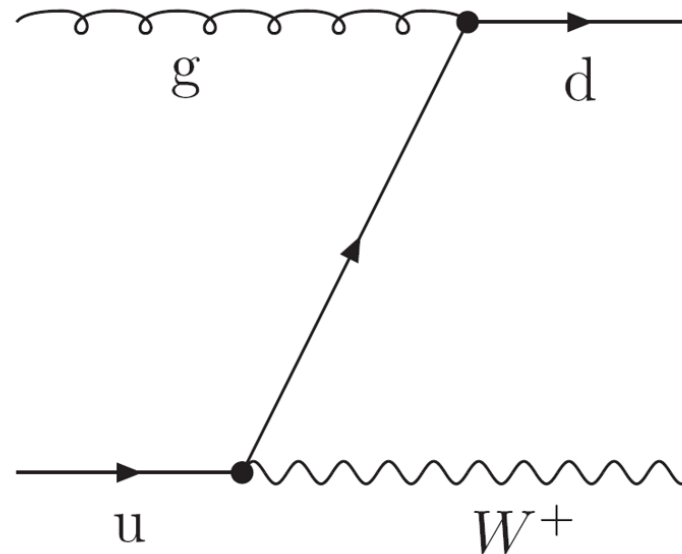
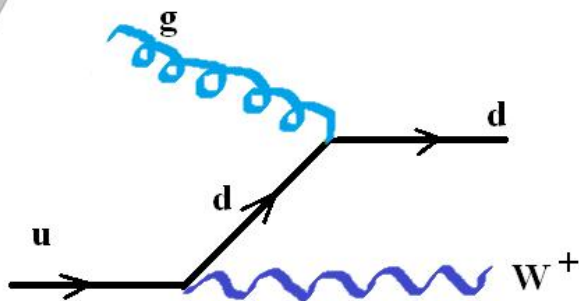
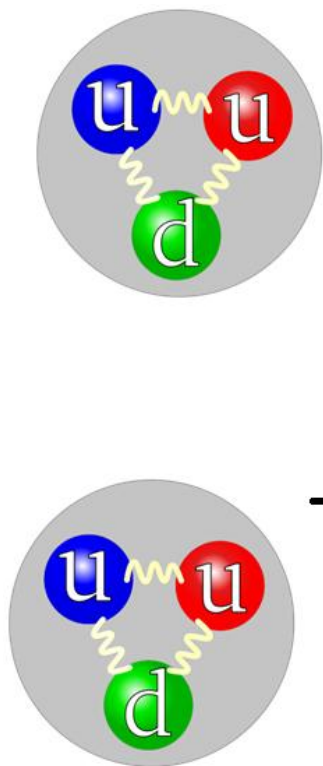


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## Strong interactions.

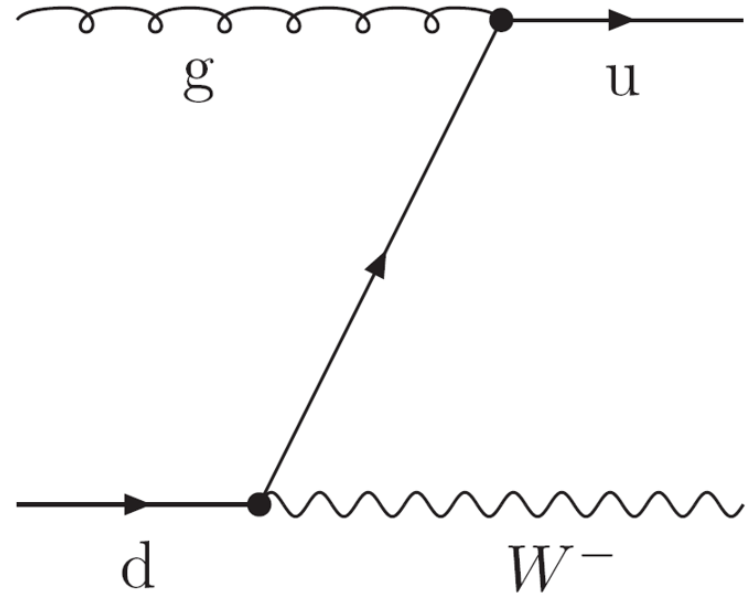
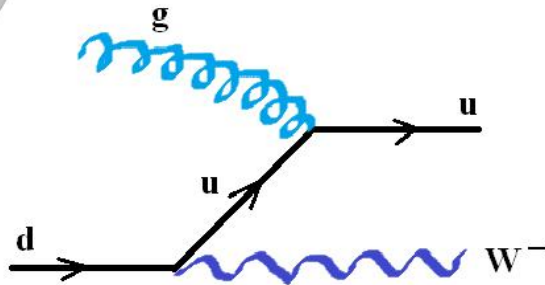
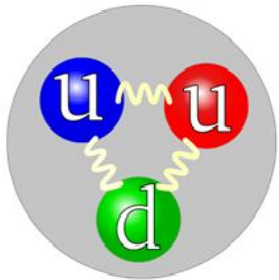
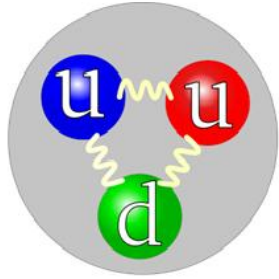
- \* Interactions between colored particles (quarks).
- \* Mediated by massless gluons  $g$  (spin one).
- \* Self interactions between gluons.
- \* Hadrons and mesons are made of quarks and gluons.
- \* At the nucleus level: binding of protons and neutrons.





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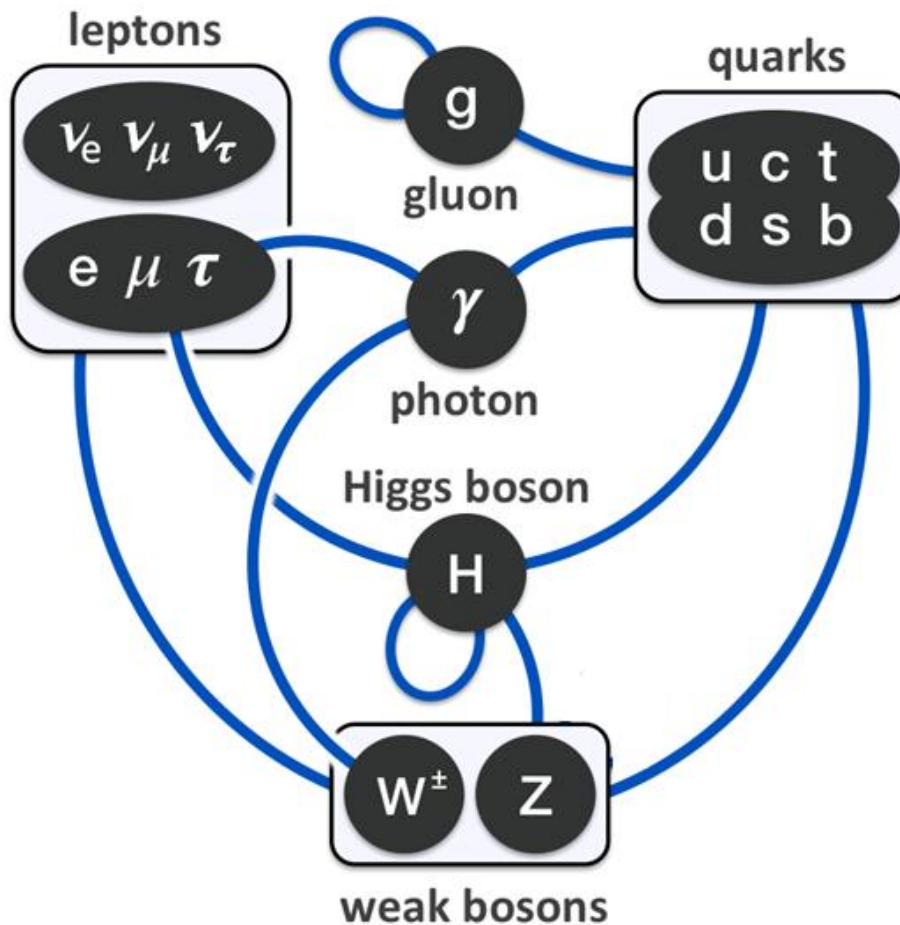


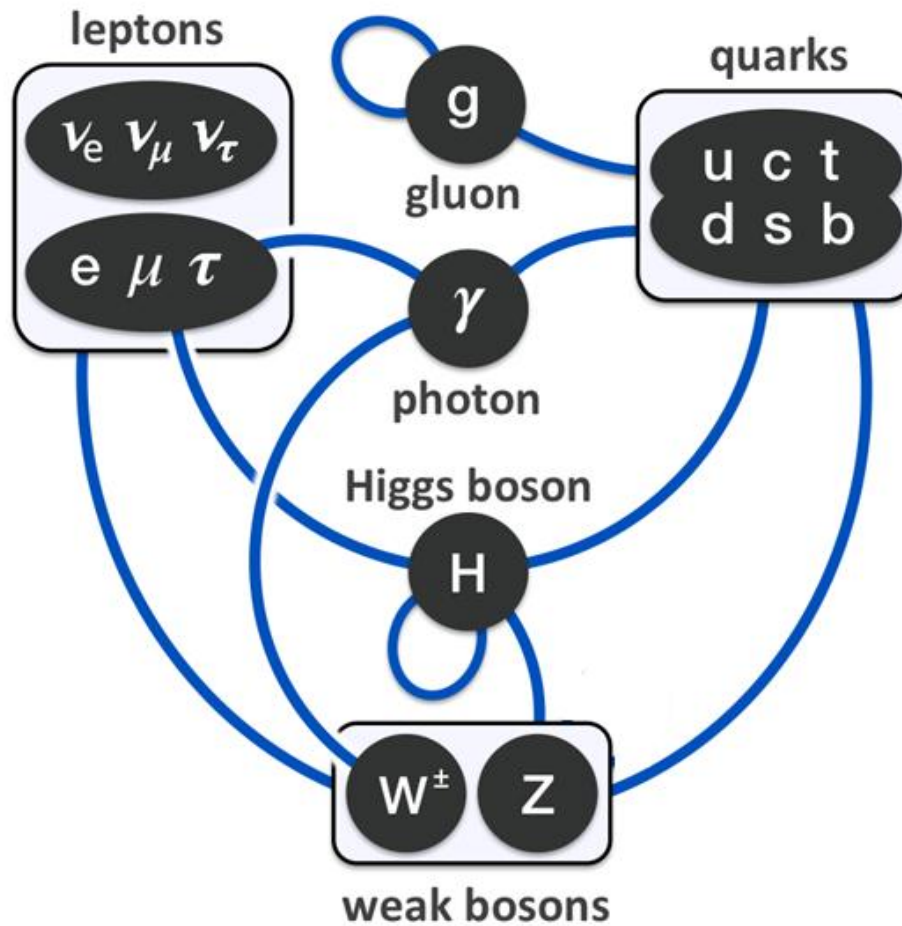


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სურათ ნაჩვენებია სქემატურად სტანდარტული მოდელის ნაწილაკების ურთიერთქმედება.

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





	<b>u</b> up	<b>c</b> charm	<b>t</b> 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

	<b>d</b> down	<b>s</b> strange	<b>b</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

	<b>e</b> electron	<b>μ</b> muon	<b>τ</b> 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

	<b>ν<sub>e</sub></b>	<b>ν<sub>μ</sub></b>	<b>ν<sub>τ</sub></b>
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

# 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:**

$\pm 1$

**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:

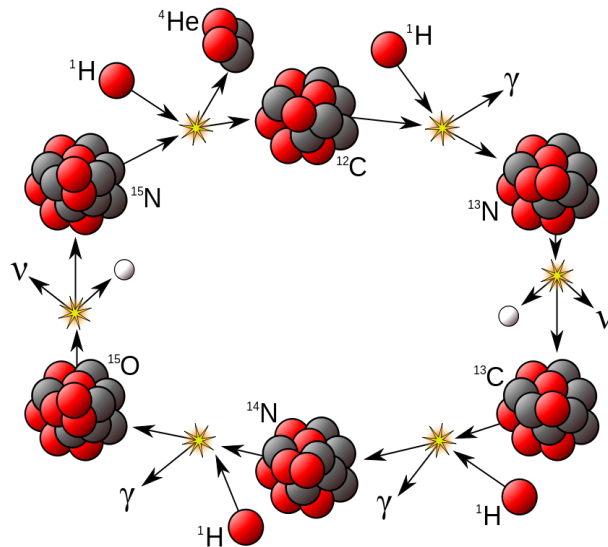
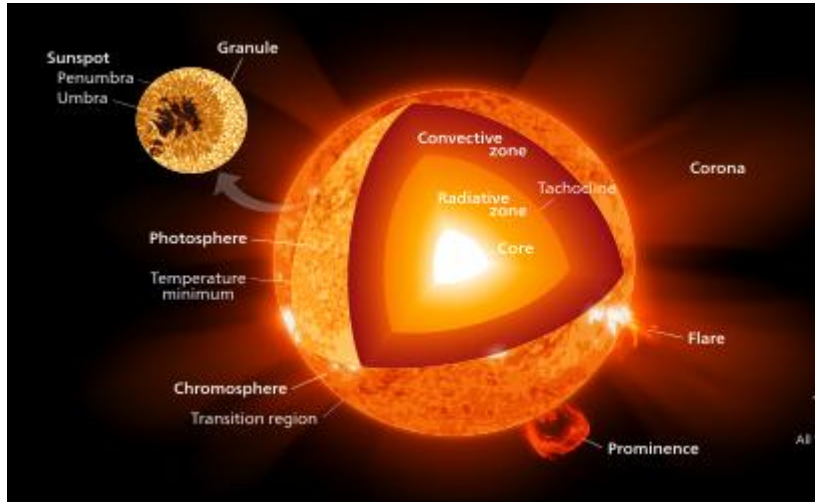
1




## About:

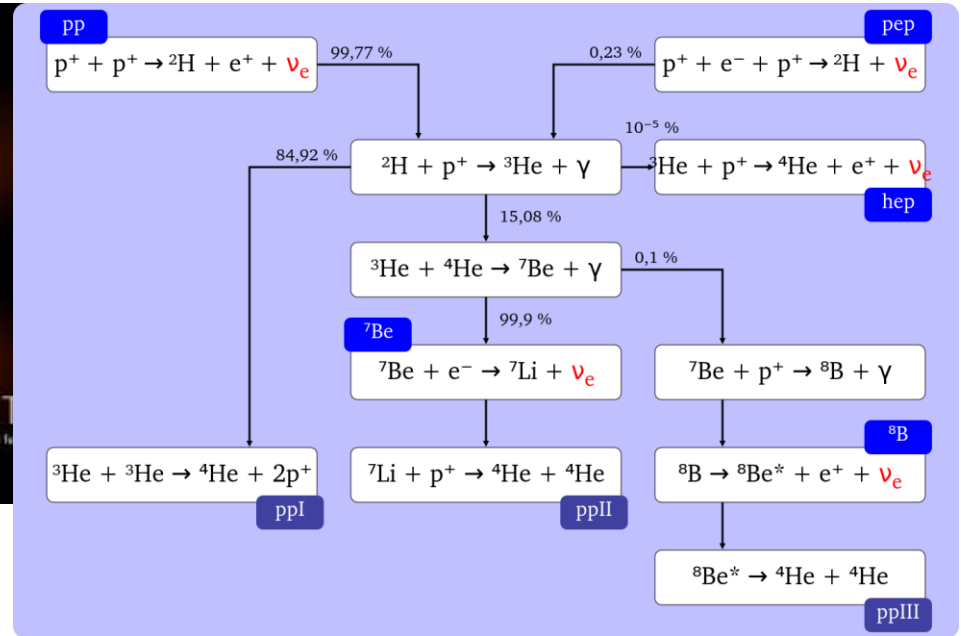
The gluon is the glue that holds together quarks to form protons, neutrons and other particles. It mediates the strong nuclear force.



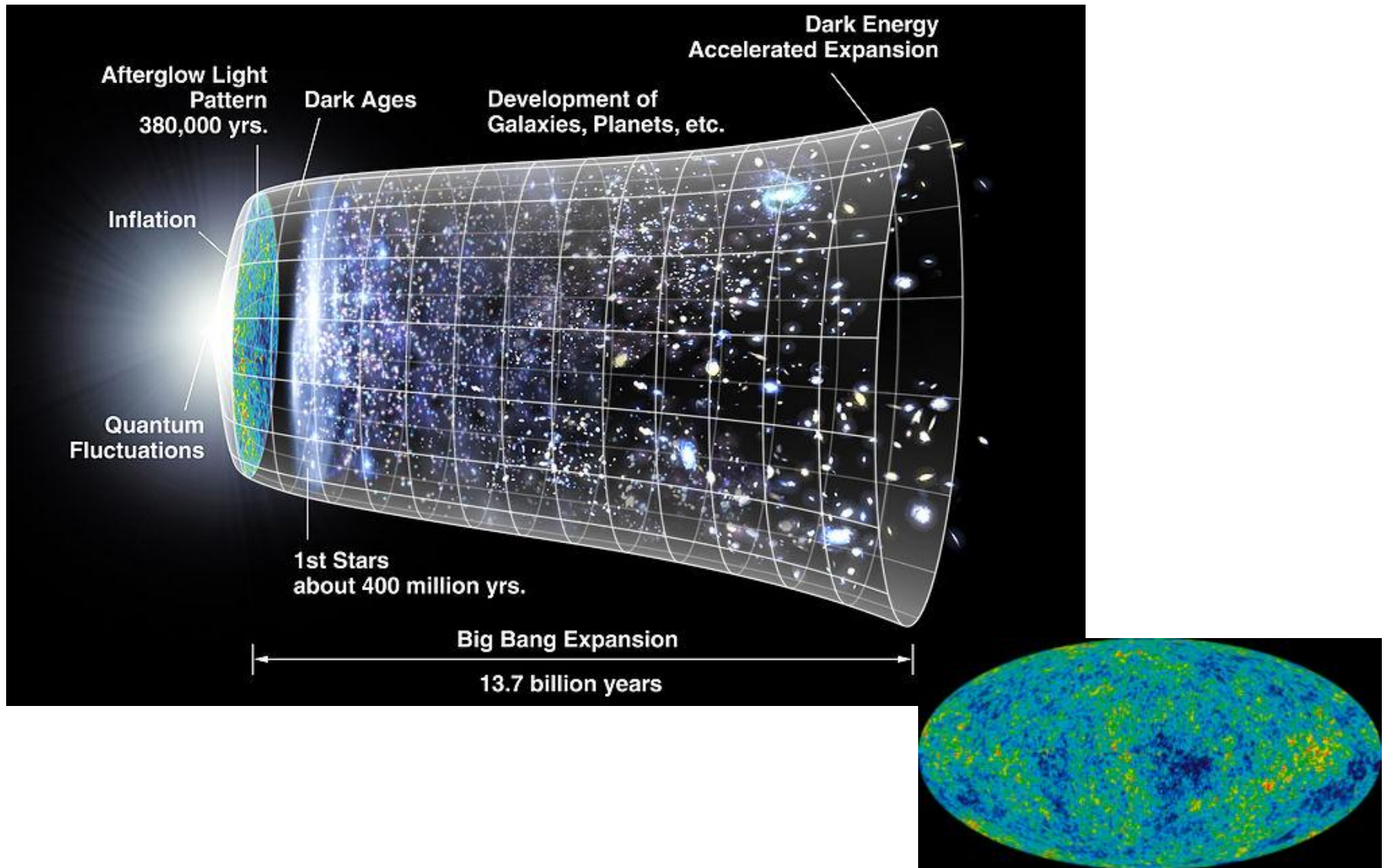
# How the Sun shines



	Proton	$\gamma$	Gamma Ray
	Neutron	$\nu$	Neutrino
	Positron		



# 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.

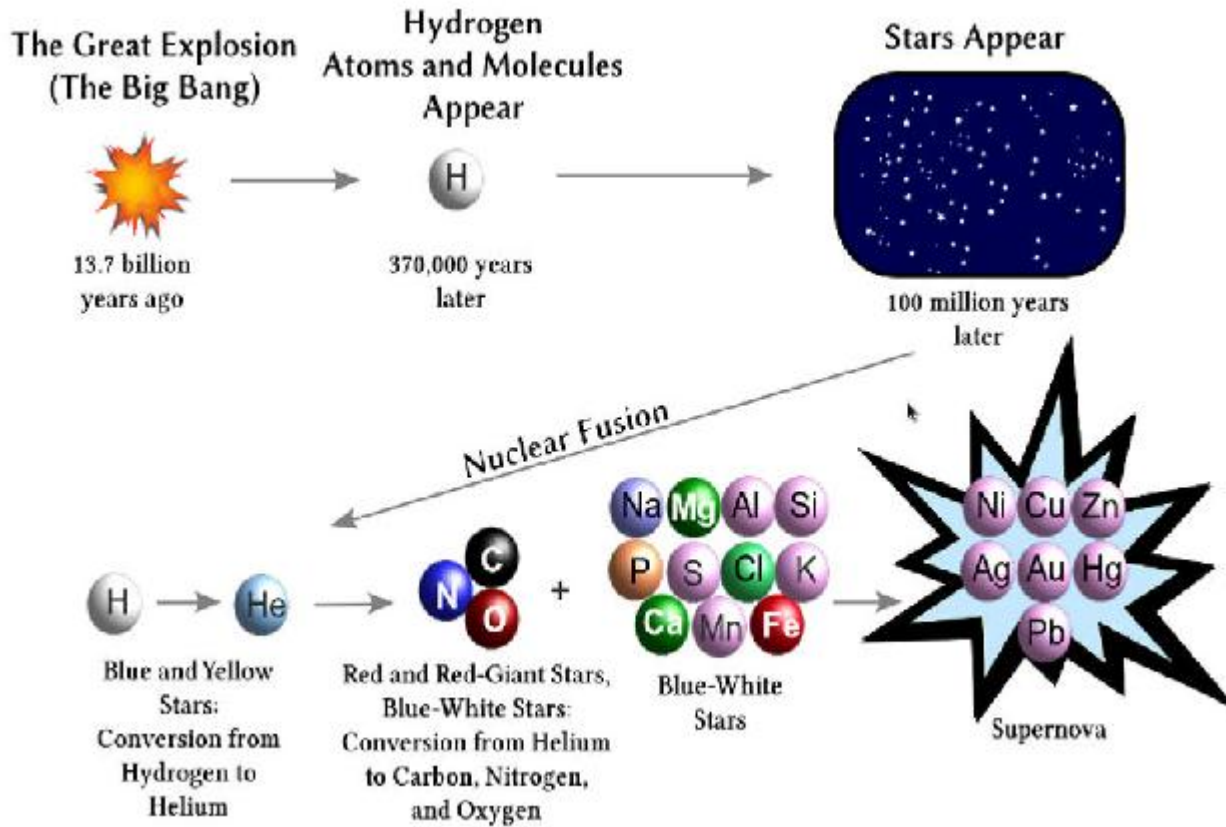
## Galaxy formation

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

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

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