INTERNATIONAL MASTERCLASSES
Hands on particle physics

Fundamental Particles in the Standard Model

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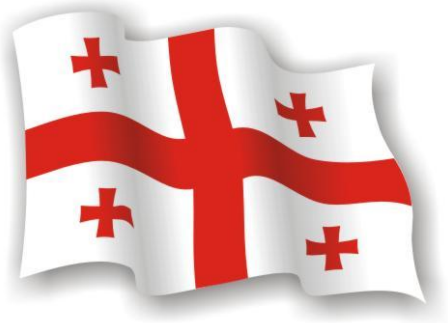

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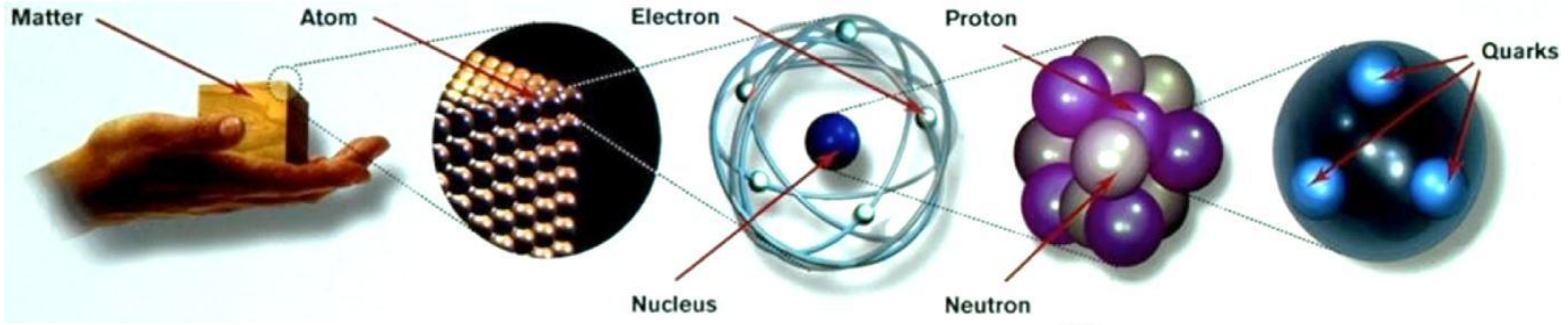
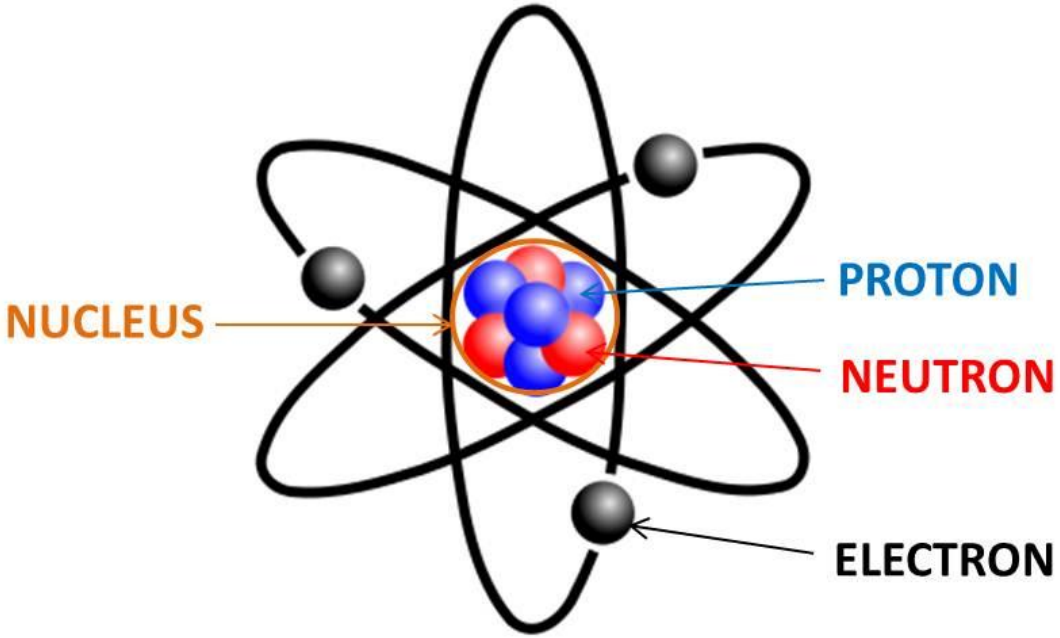
Tbilisi, Georgia

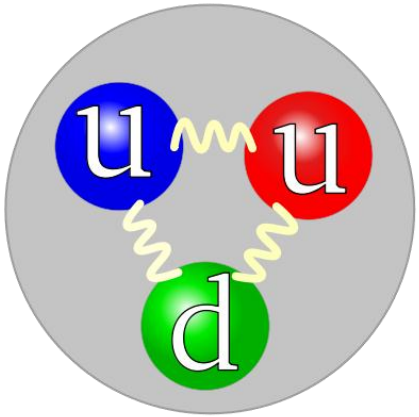


- **Atom**



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

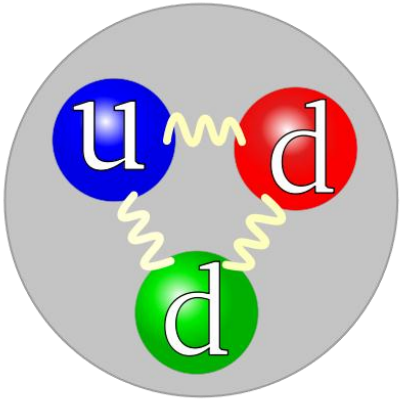
Proton



⅔ + ⅔ – ⅓ = 1

u u d

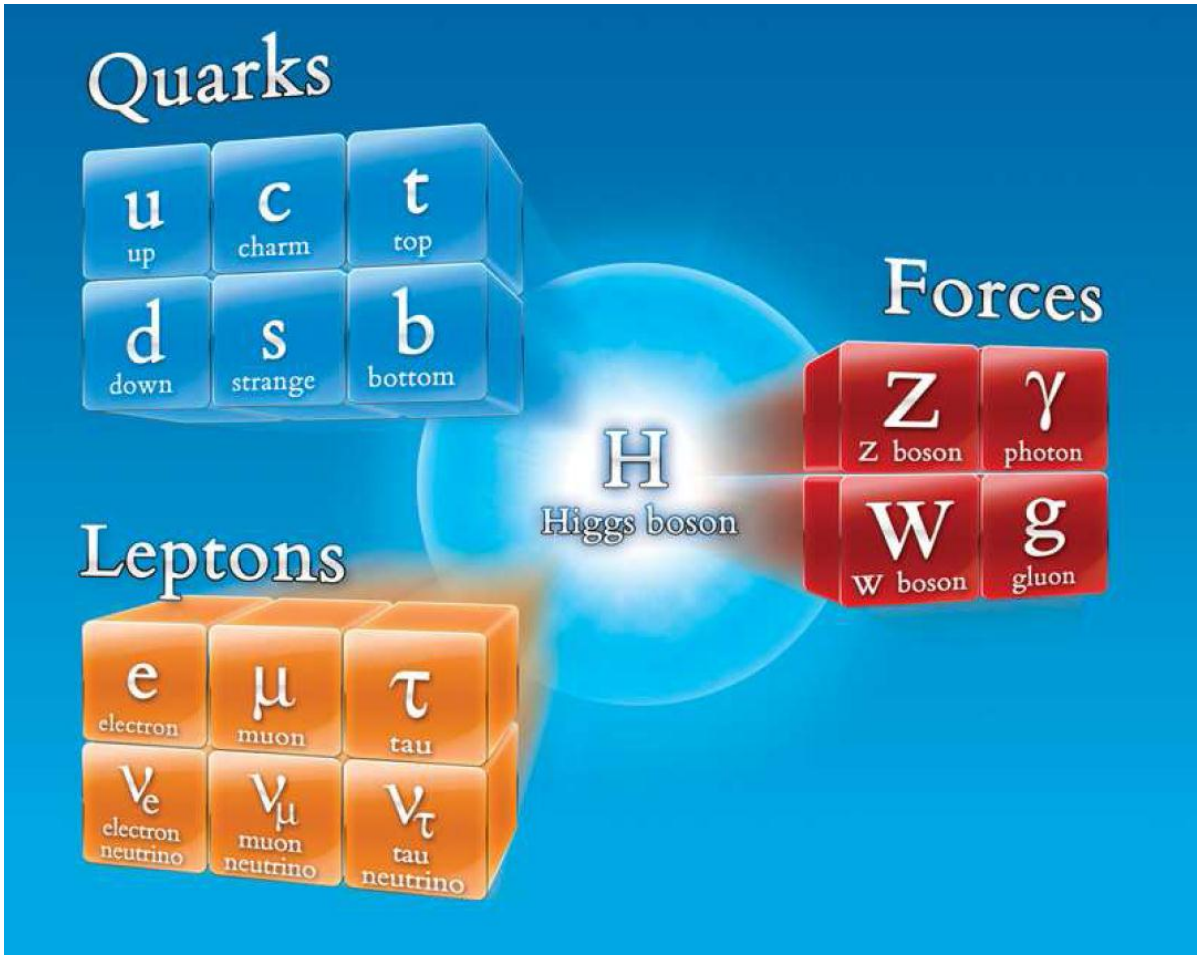
Neutron

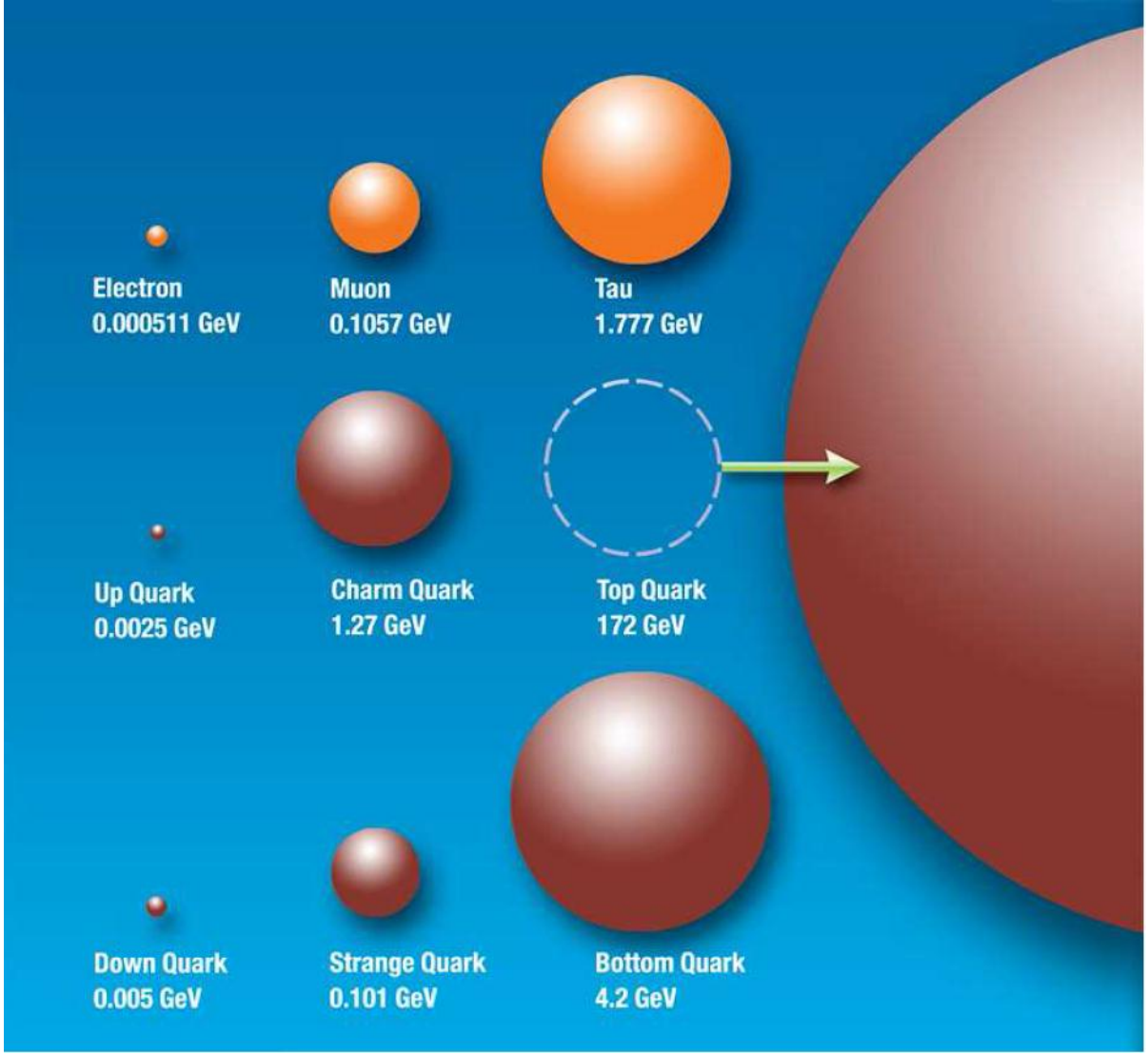


⅔ – ⅓ – ⅓ = 0

u d d

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

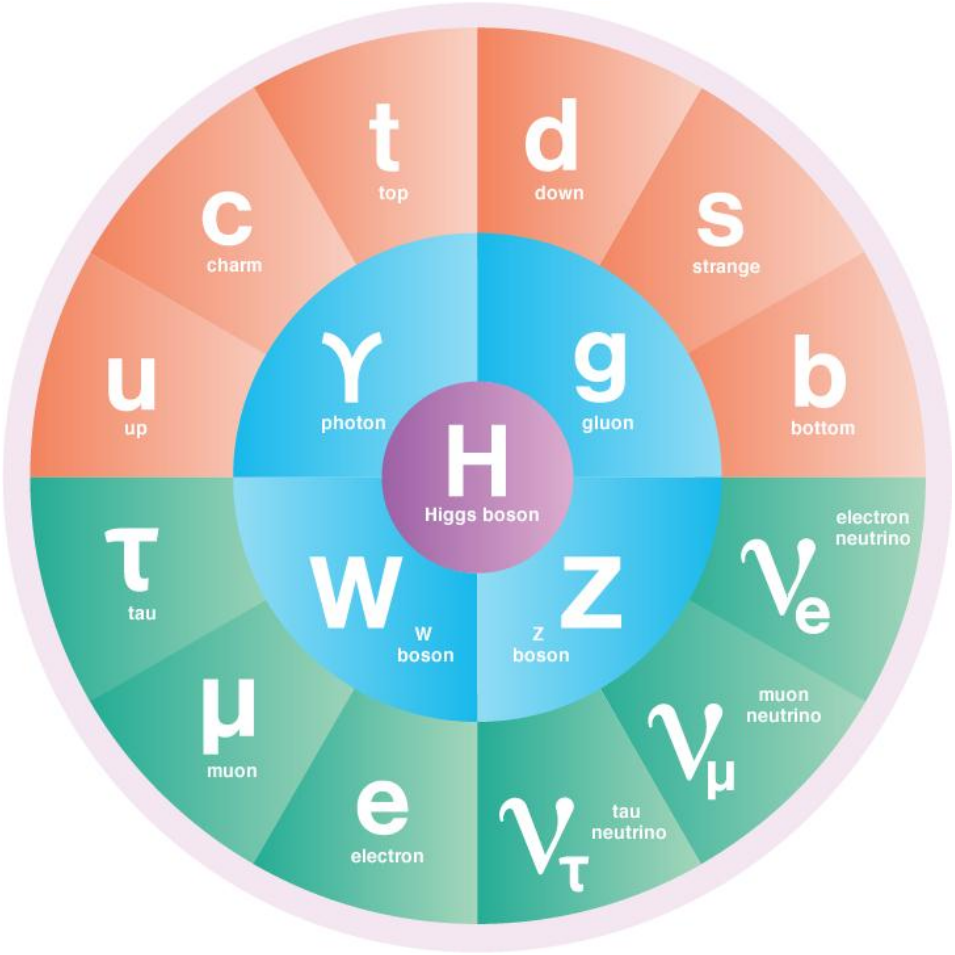

Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Leptons
e
electron
μ
muon
τ
tau
νe
electron neutrino
νμ
muon neutrino
ντ
tau neutrino
H
Higgs boson
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon



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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charm
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H
Higgs boson
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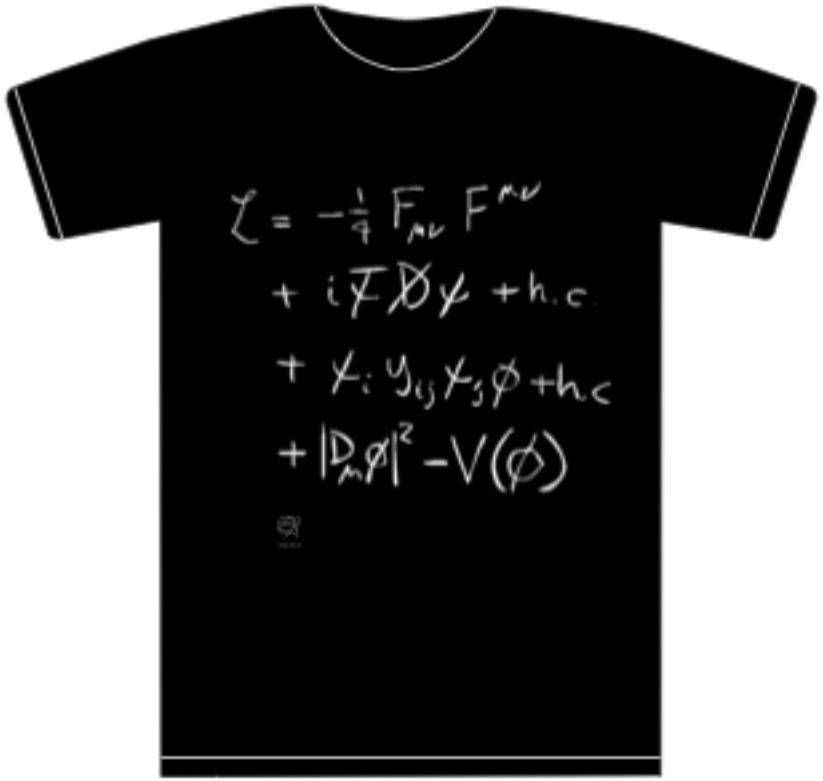
tau
electron
neutrino
W
W
boson
Z
Z
boson
μ
muon
muon
neutrino
e
electron
tau
neutrino

*** 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

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



The Standard Model Lagranjian in detail

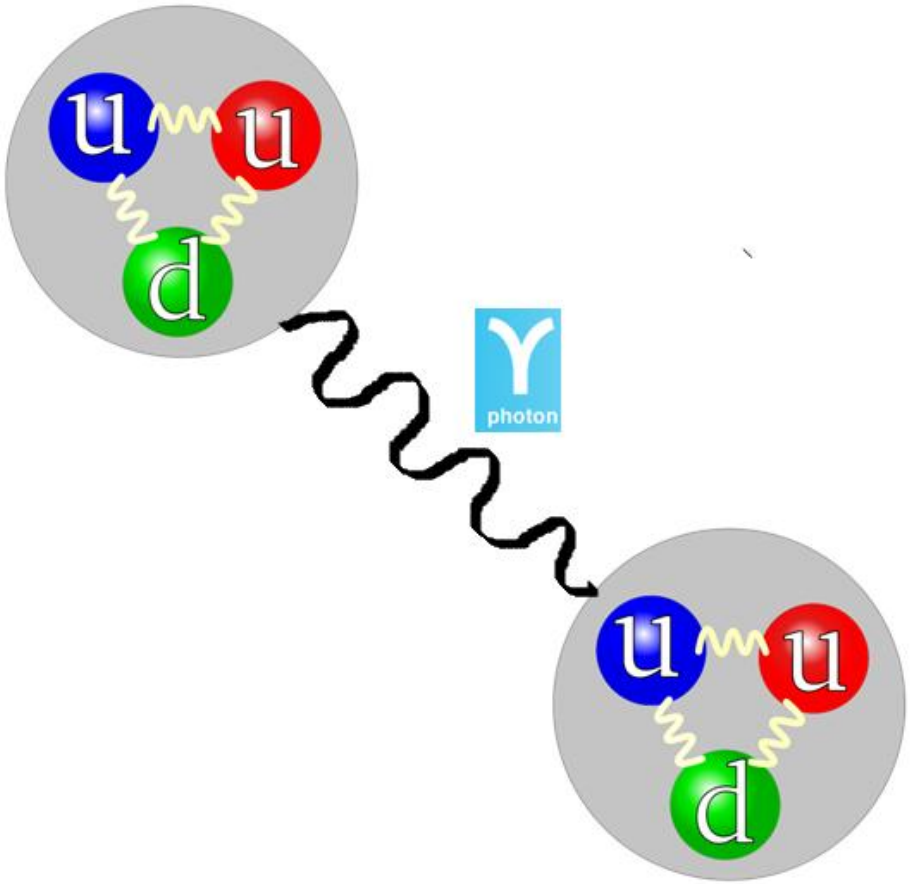
$$
\begin{aligned}
&\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
&M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
&igs_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)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
&Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
&W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
&\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-) \right) + \tfrac{2M^4}{g^2}\alpha_h - \\
&g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^- \right) - \\
&\tfrac{1}{8}g^2 \alpha_h \left(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 \right) - \\
&gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \\
&\tfrac{1}{2}ig\left(W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0) \right) + \\
&\tfrac{1}{2}g\left(W^+_\mu (H\partial_\mu \phi^- - \phi^- \partial_\mu H) + W^-_\mu (H\partial_\mu \phi^+ - \phi^+ \partial_\mu H) \right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
&M\left(\tfrac{1}{c_w} Z^0_\mu \partial_\mu \phi^0 + W^+_\mu \partial_\mu \phi^- + W^-_\mu \partial_\mu \phi^+ \right) - ig\tfrac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w M A_\mu (W^+_\mu \phi^- - \\
&W^-_\mu \phi^+) - ig\tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
&\tfrac{1}{4}g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^- \right) - \tfrac{1}{8}g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^- \right) - \\
&\tfrac{1}{2}g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \tfrac{1}{2}ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
&W^-_\mu \phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu \phi^+ \phi^- - \\
&g^2 s_w^2 A_\mu A_\mu \phi^+ \phi^- + \tfrac{1}{2}ig_s \lambda^a_{ij} (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda (\gamma\partial + m^\lambda_\nu) \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + \\
&m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + igs_w A_\mu \left(-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j) \right) + \\
&\tfrac{ig}{4c_w} Z^0_\mu \{ (\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}^\lambda_j \gamma^\mu (\tfrac{4}{3}s_w^2 - 1 - \gamma^5) d^\lambda_j) + \\
&(\bar{u}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3}s_w^2 + \gamma^5) u^\lambda_j) \} + \tfrac{ig}{2\sqrt{2}} W^+_\mu \left((\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) U^{lep}_{\lambda\kappa} e^\kappa) + (\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j) \right) + \\
&\tfrac{ig}{2\sqrt{2}} W^-_\mu \left((\bar{e}^\kappa U^{lep\,\dagger}_{\kappa\lambda} \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda} \gamma^\mu (1+\gamma^5) u^\lambda_j) \right) + \\
&\tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_e (\bar{\nu}^\lambda U^{lep}_{\lambda\kappa} (1-\gamma^5) e^\kappa) + m^\lambda_\nu (\bar{\nu}^\lambda U^{lep}_{\lambda\kappa} (1+\gamma^5) e^\kappa) \right) + \\
&\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_e (\bar{e}^\lambda U^{lep\,\dagger}_{\lambda\kappa} (1+\gamma^5) \nu^\kappa) - m^\kappa_\nu (\bar{e}^\lambda U^{lep\,\dagger}_{\lambda\kappa} (1-\gamma^5) \nu^\kappa) \right) - \tfrac{g}{2}\tfrac{m^\lambda_e}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
&\tfrac{g}{2}\tfrac{m^\lambda_e}{M} H (\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_e}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \tfrac{1}{4}\,\bar{\nu}_\lambda\, M^R_{\lambda\kappa}\, (1-\gamma_5) \hat{\nu}_\kappa - \\
&\tfrac{1}{4}\,\overline{\bar{\nu}_\lambda\, M^R_{\lambda\kappa}\, (1-\gamma_5) \hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j) \right) + \\
&\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1-\gamma^5) u^\kappa_j) \right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \\
&\tfrac{g}{2}\tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu + \\
&\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{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) + igs_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^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \\
&\partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
&\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2}gM \left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H \right) + \tfrac{1-2c_w^2}{2c_w} igM \left(\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^- \right) + \\
&\tfrac{1}{2c_w} igM \left(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + igMs_w \left(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + \\
&\tfrac{1}{2}igM \left(\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0 \right) .
\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 particules.**
  - *** 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).**

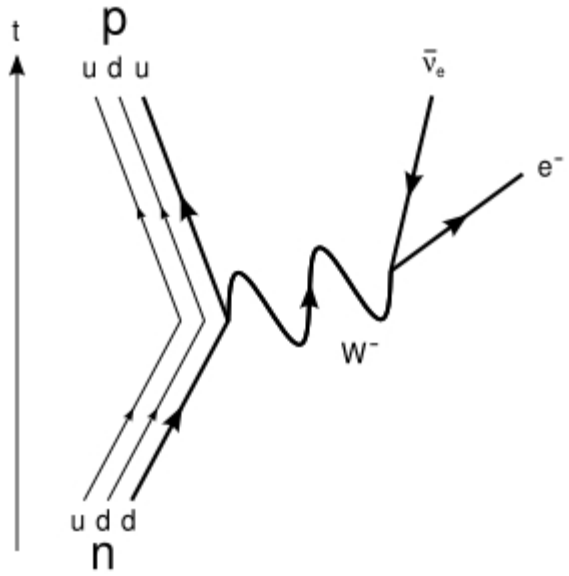


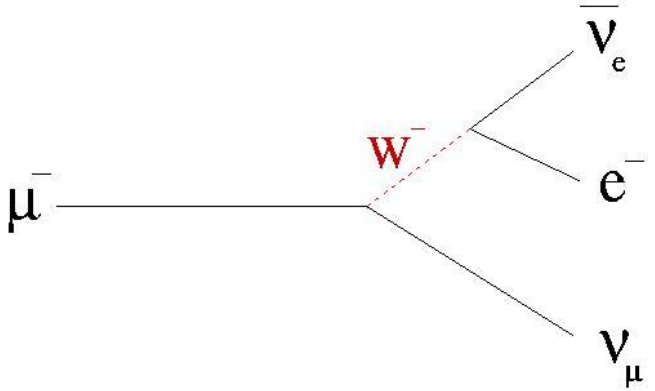
Weak interaction.

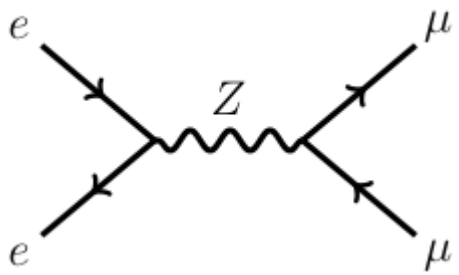
*** Interactions between the left-handed components of the fermions.**

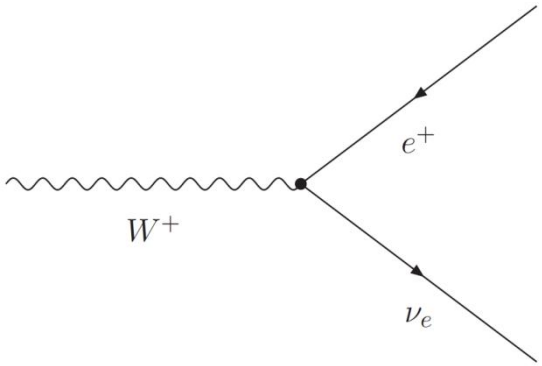
*** Mediated by massive weak bosons W and Z.**

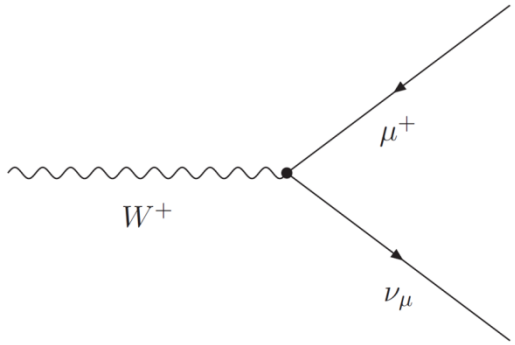
*** Self interactions between W and Z bosons**

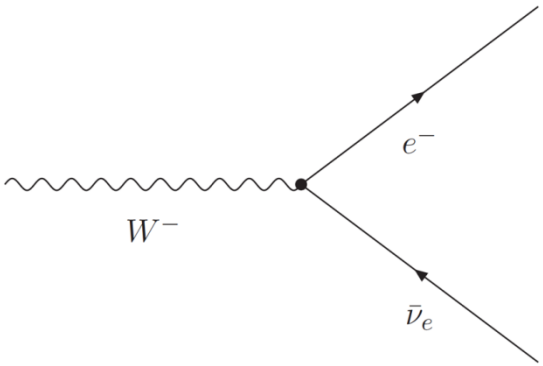


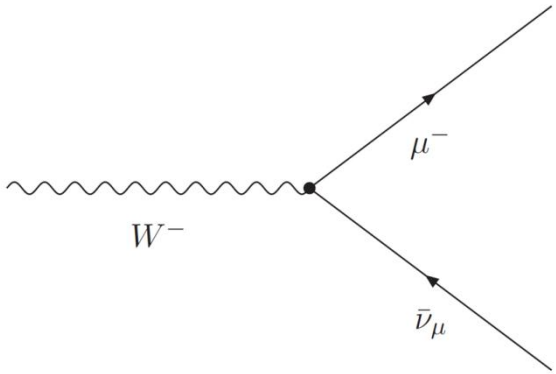





e^+
W^+
ν_e

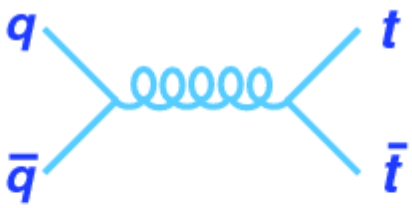

μ^+
W^+
ν_μ

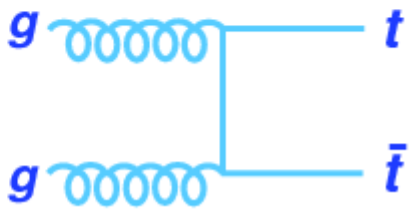

e^-
W^-
$\bar{\nu}_e$

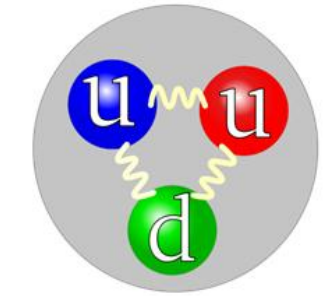

μ^-
W^-
$\bar{\nu}_\mu$

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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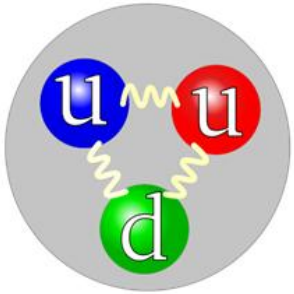
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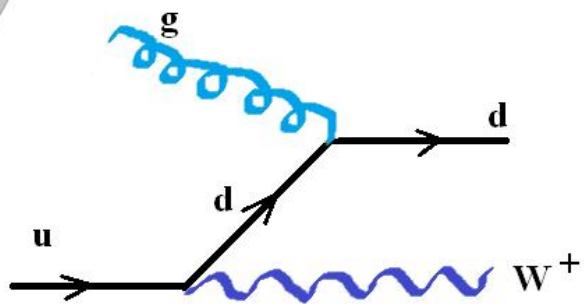
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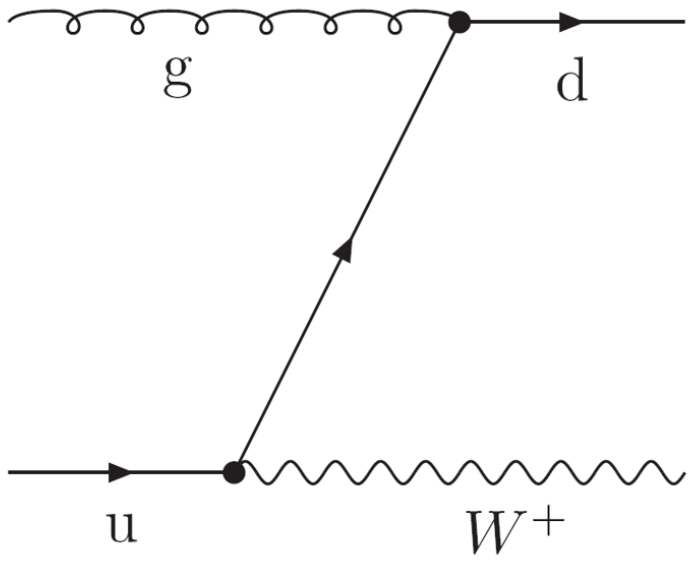
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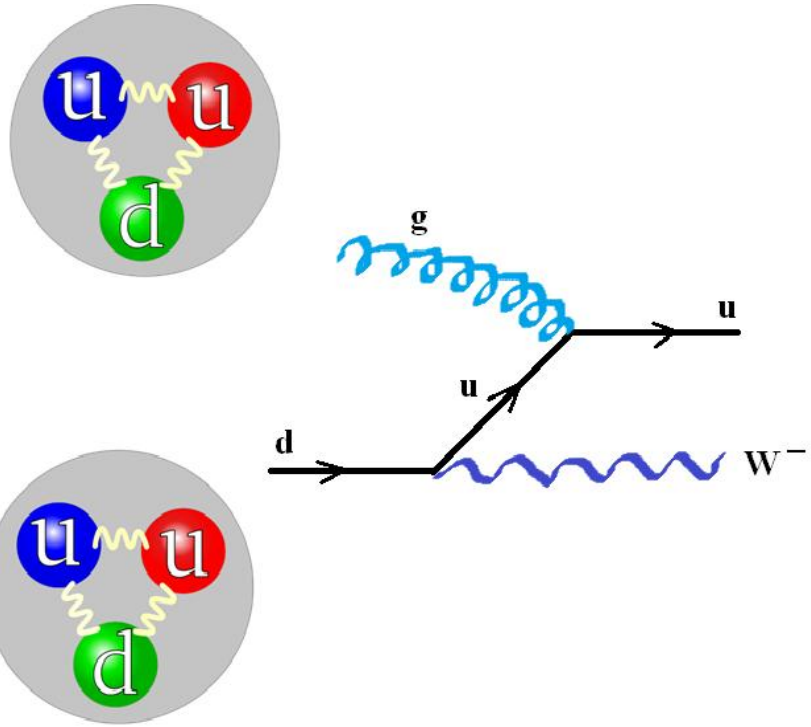
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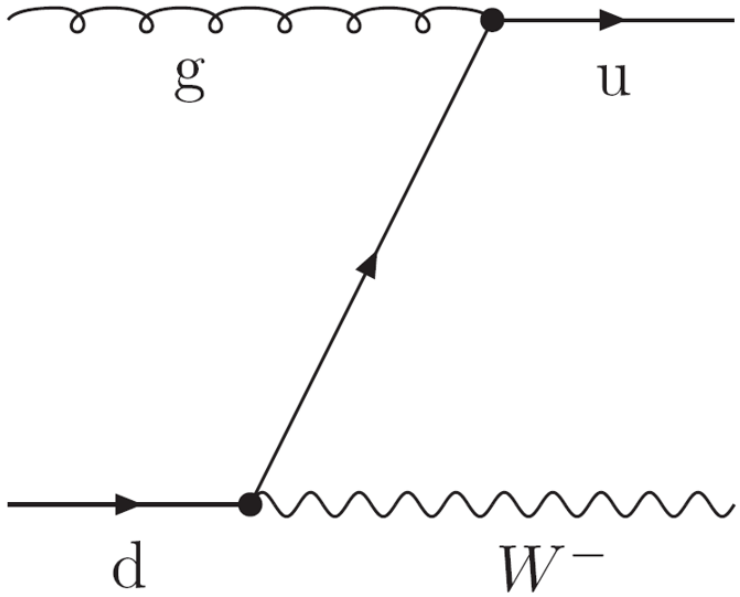
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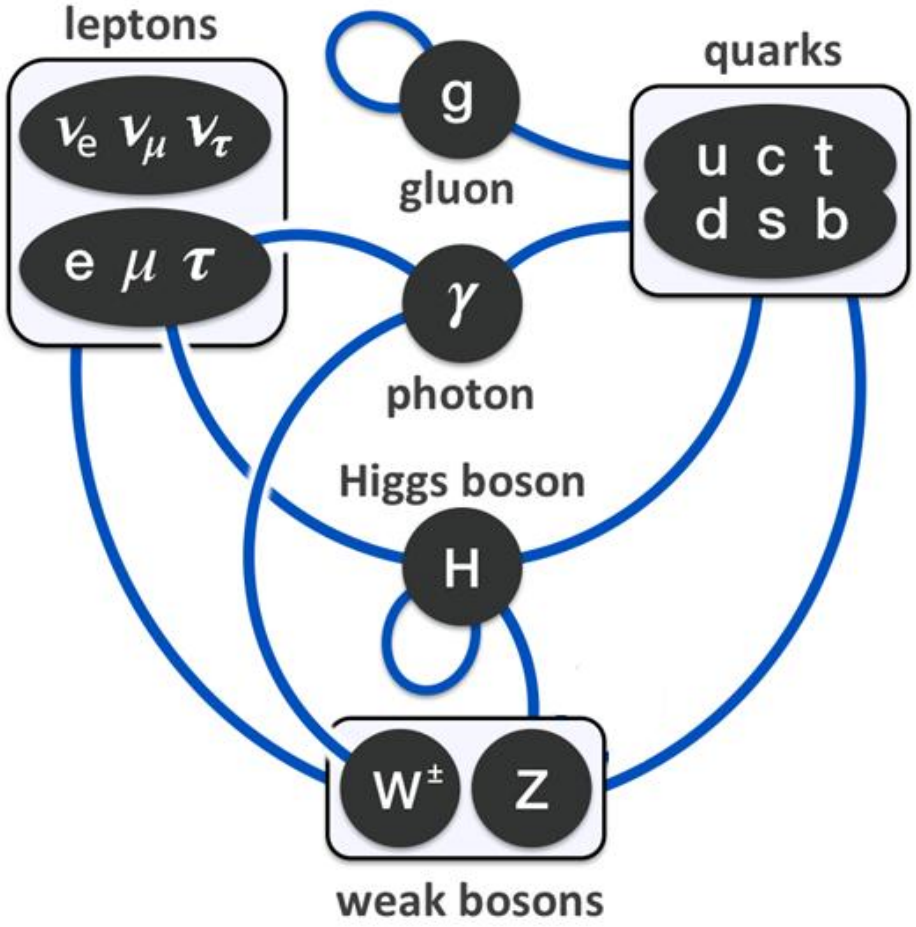

leptons
ν_e ν_μ ν_τ
e μ τ
g
gluon
quarks
u c t
d s b
γ
photon
Higgs boson
H
W±
Z
weak bosons

	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

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

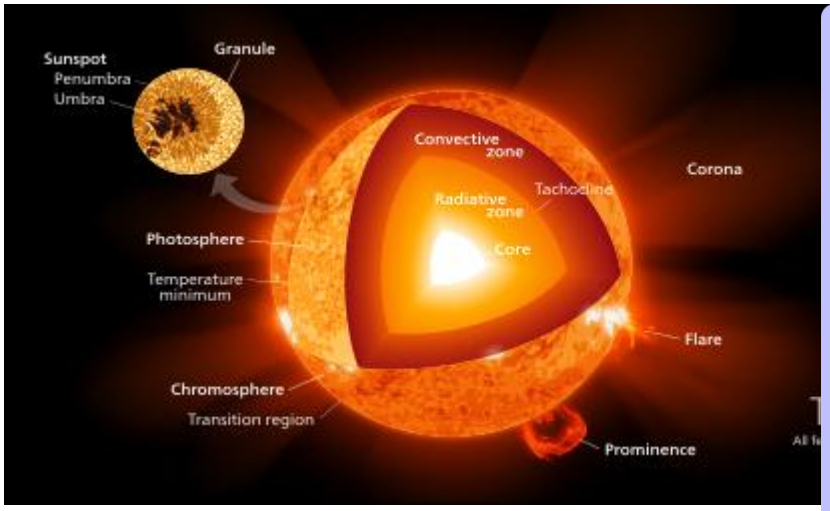
Spin:

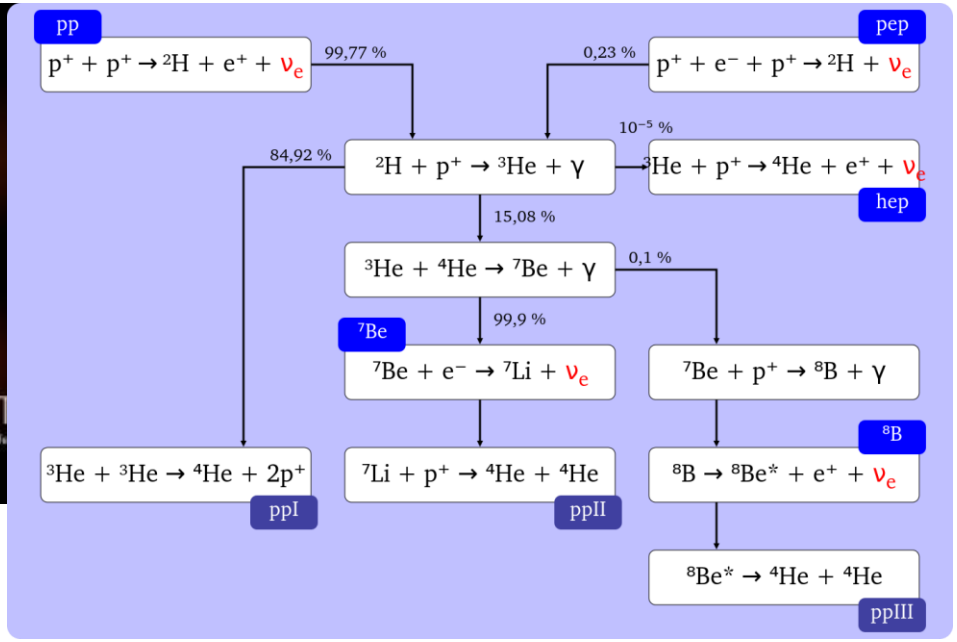
1

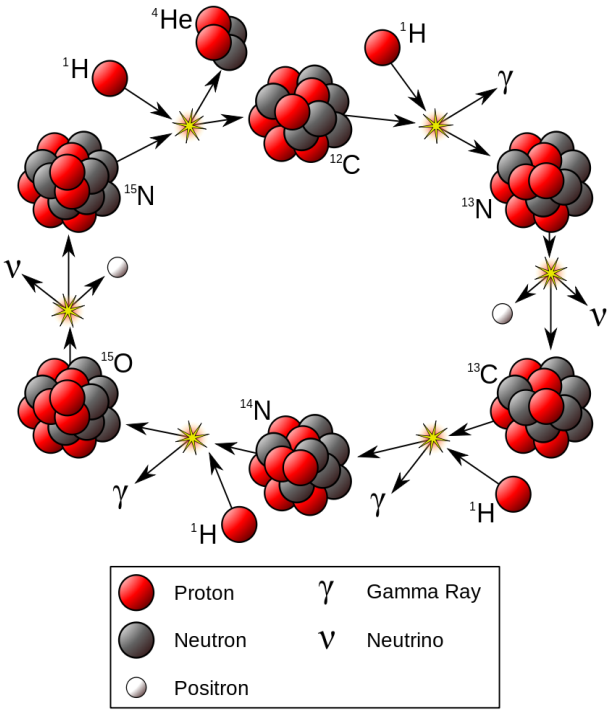
About:

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

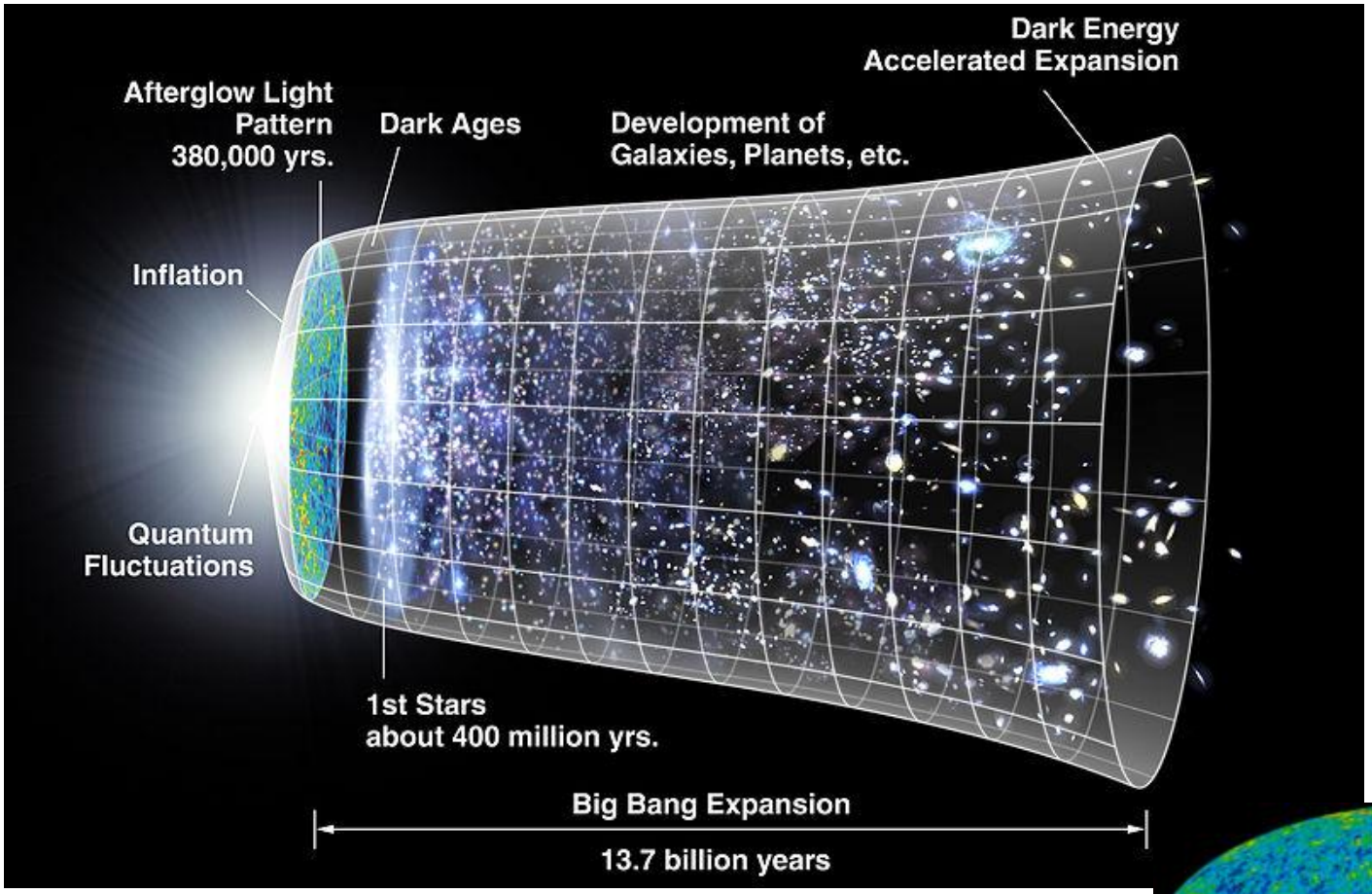
How the Sun shines

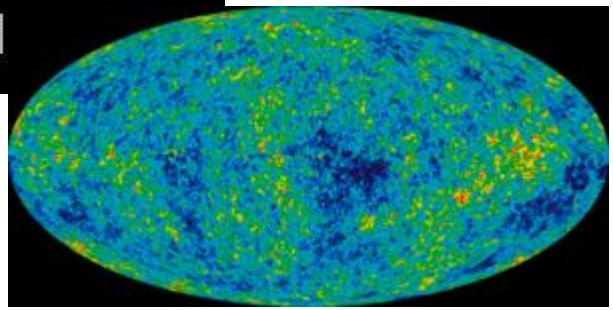


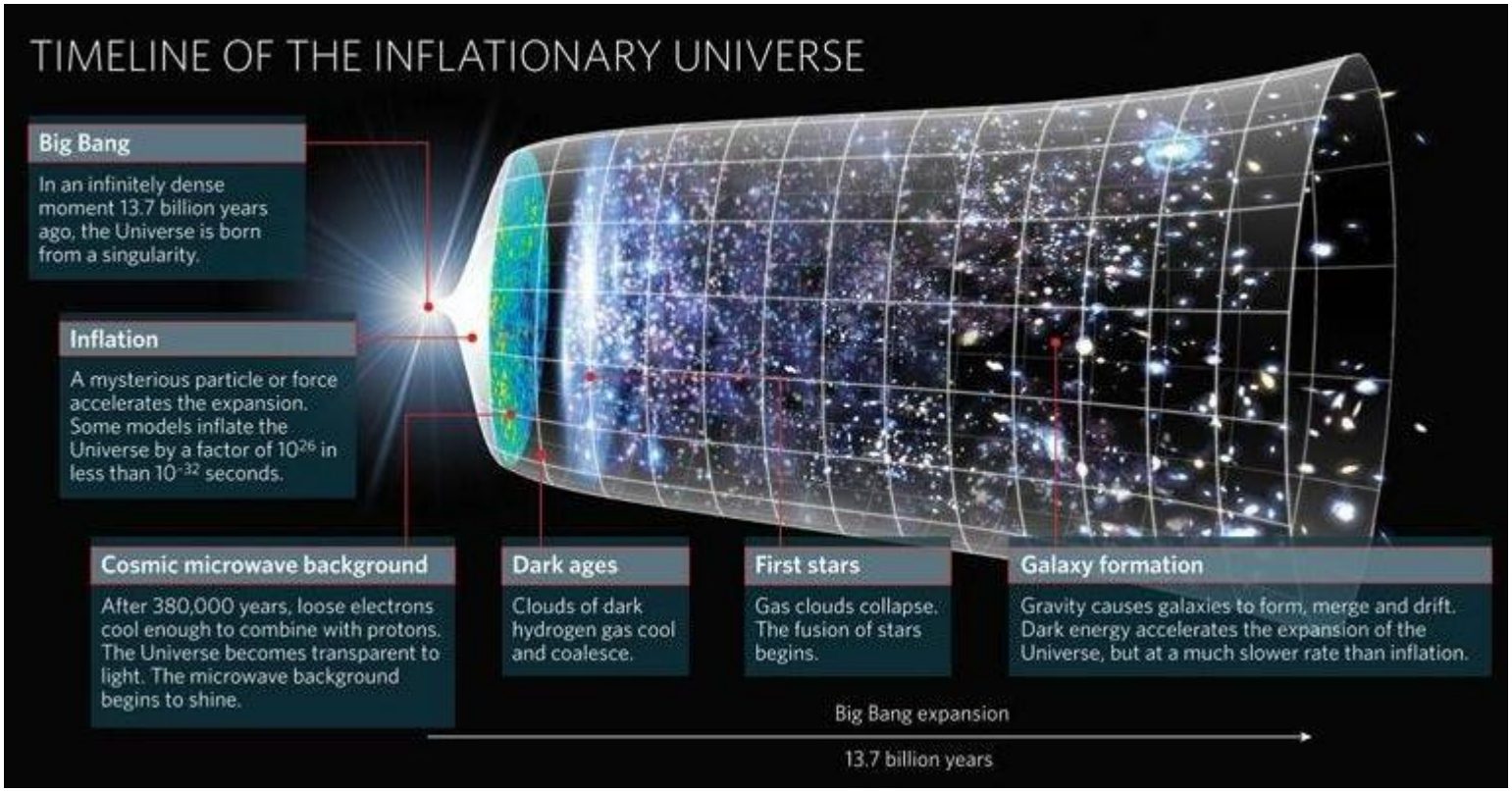


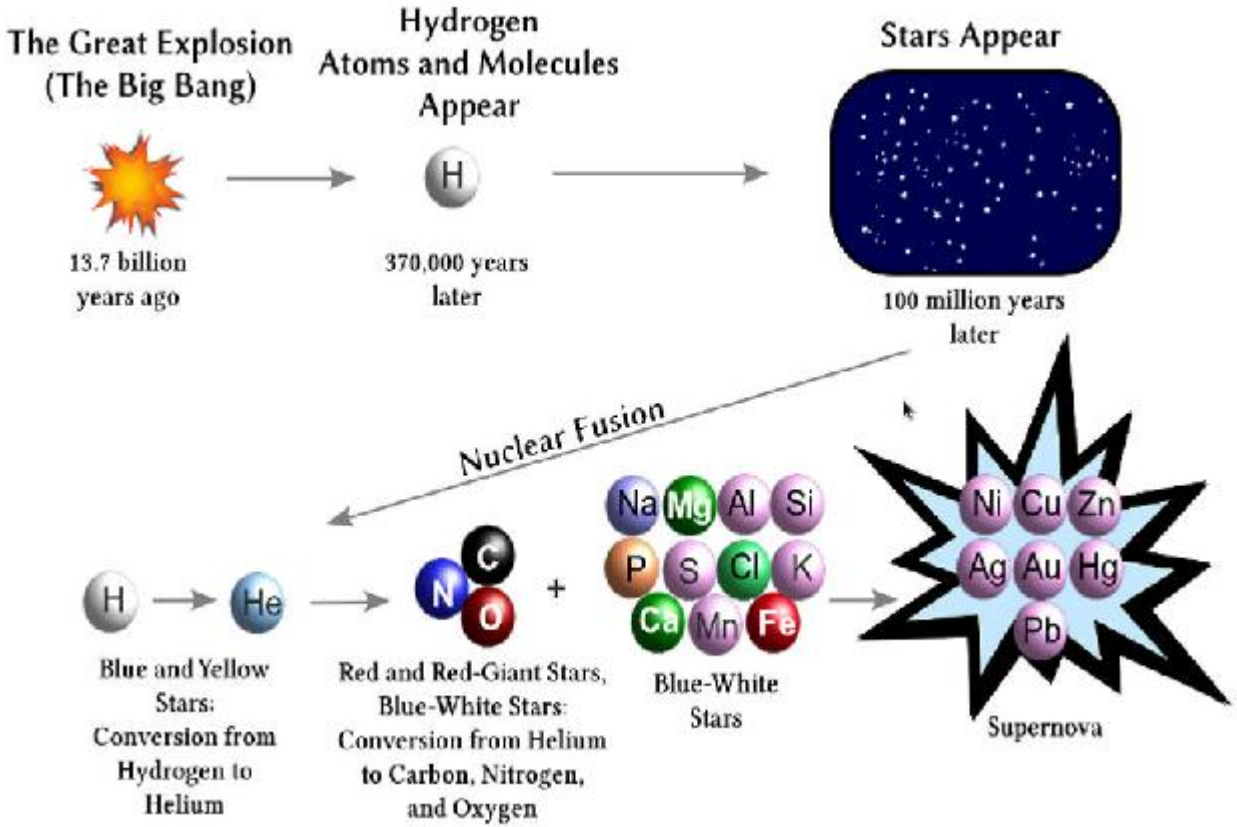


The Universe made selfie






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



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