

# INTERNATIONAL MASTERCLASSES

## Hands on particle physics

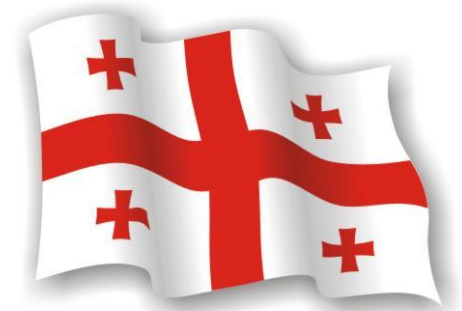
### Fundamentals of Particle Physics

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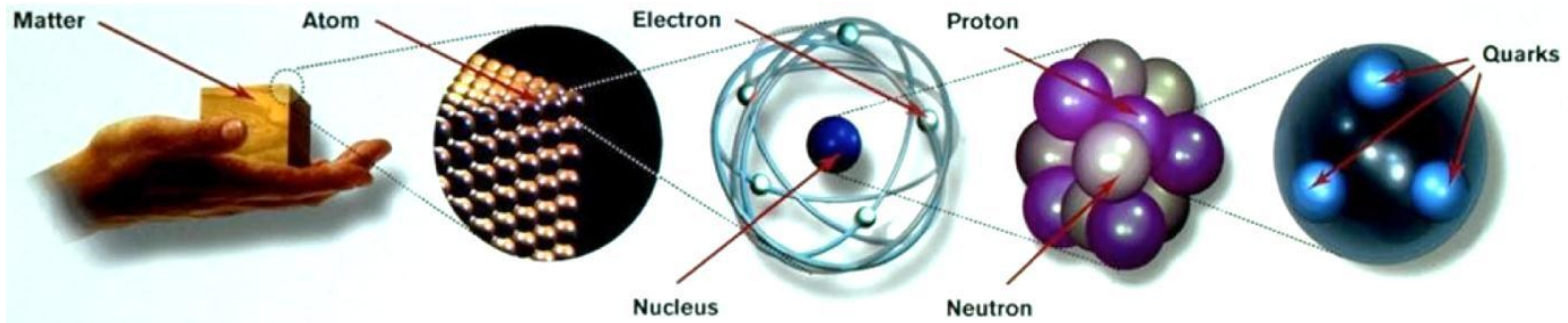
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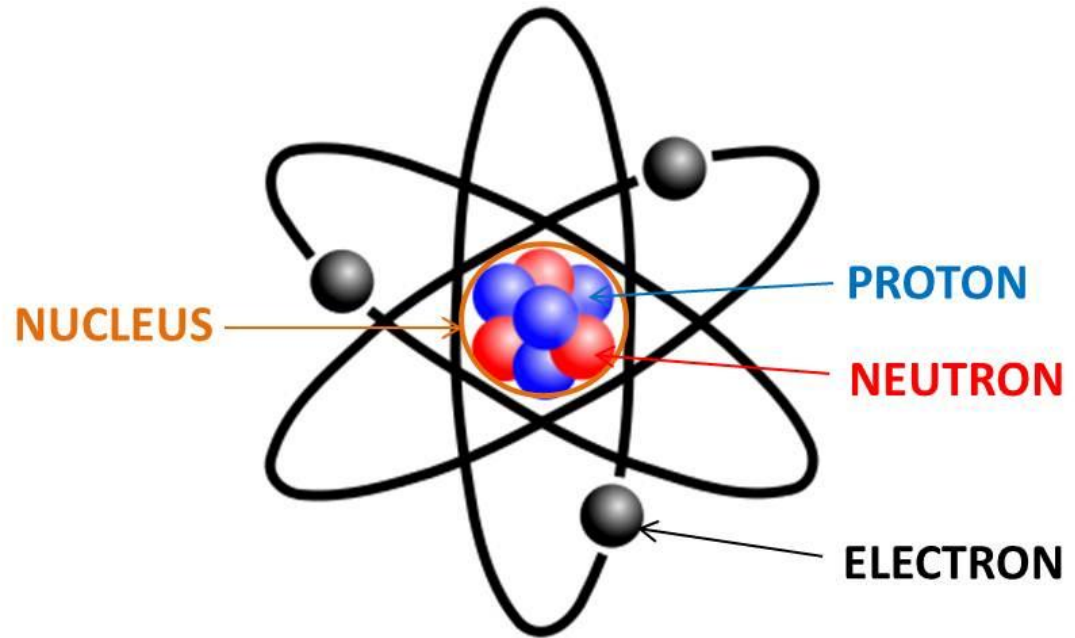


**March 10, 2018**  
**Tbilisi, Georgia**

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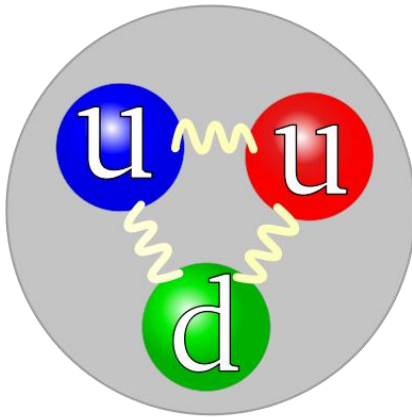


- **Atom**



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

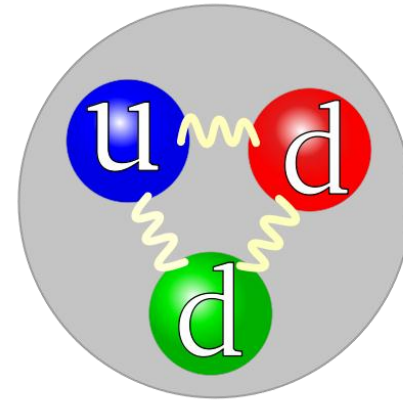
## Proton



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

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.

**Only 30% of proton energy is carried by the three constituent uud quarks**

**Most of proton energy is carried by gluons**

# Quarks

<b>u</b> up	<b>c</b> charm	<b>t</b> top
<b>d</b> down	<b>s</b> strange	<b>b</b> bottom

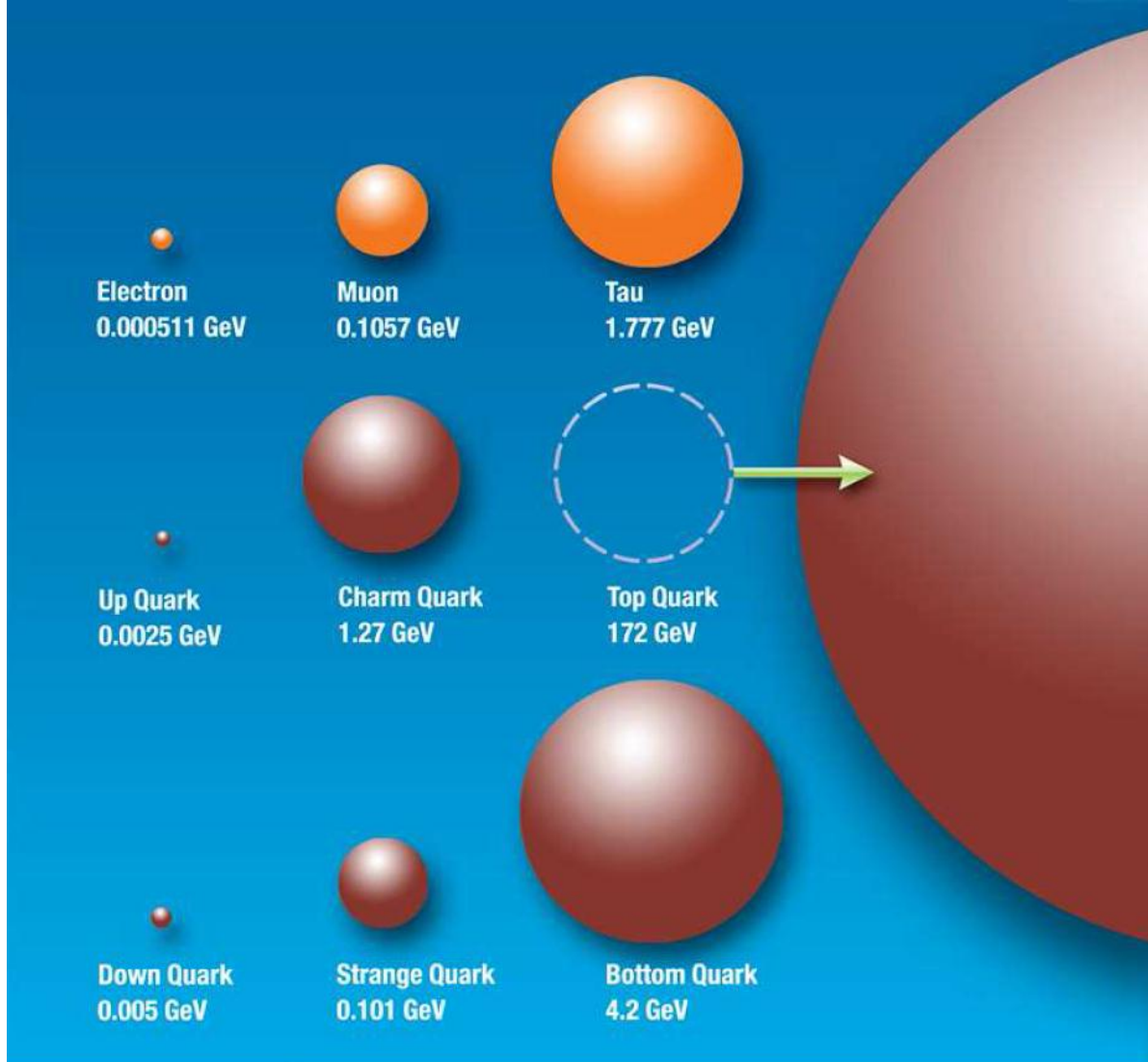
# Leptons

<b>e</b> electron	<b><math>\mu</math></b> muon	<b><math>\tau</math></b> tau
<b><math>\nu_e</math></b> electron neutrino	<b><math>\nu_\mu</math></b> muon neutrino	<b><math>\nu_\tau</math></b> tau neutrino

# Forces

<b>Z</b> Z boson	<b><math>\gamma</math></b> photon
<b>W</b> W boson	<b>g</b> gluon

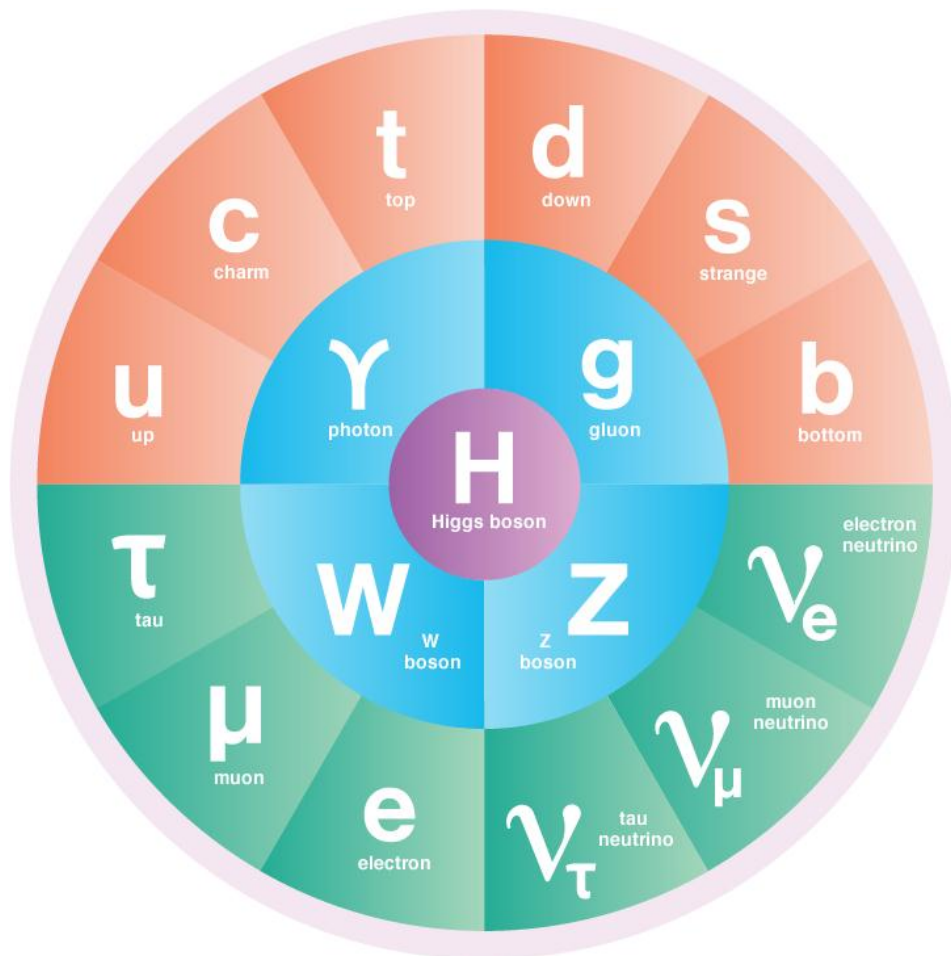
**H**  
Higgs boson



**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 particles have been observed.**

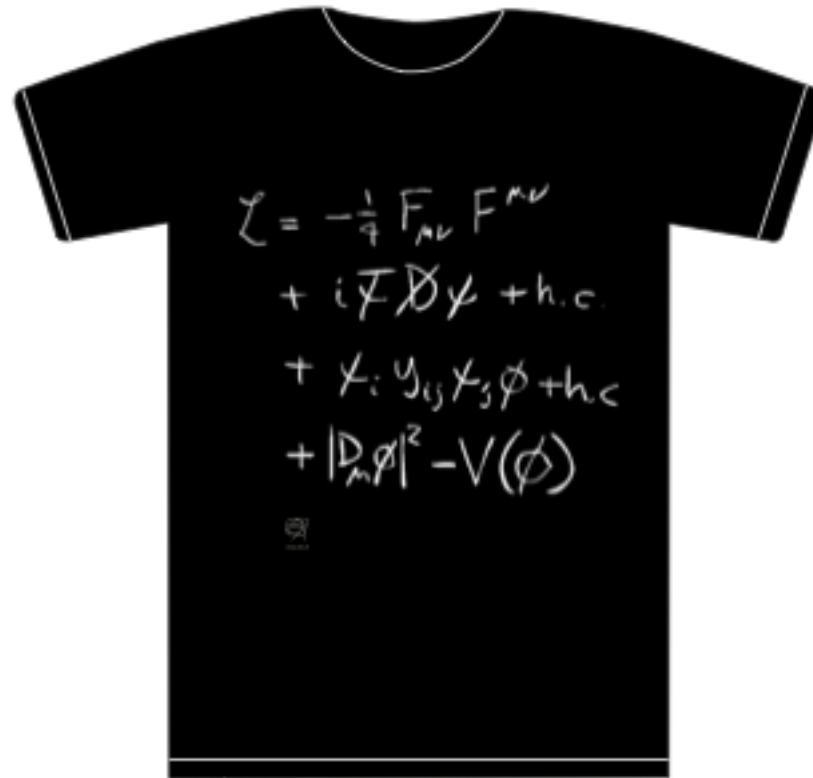
**\* Last ones: top quark (1995), tau neutrino (2000) and Higgs Boson (2012).**



**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

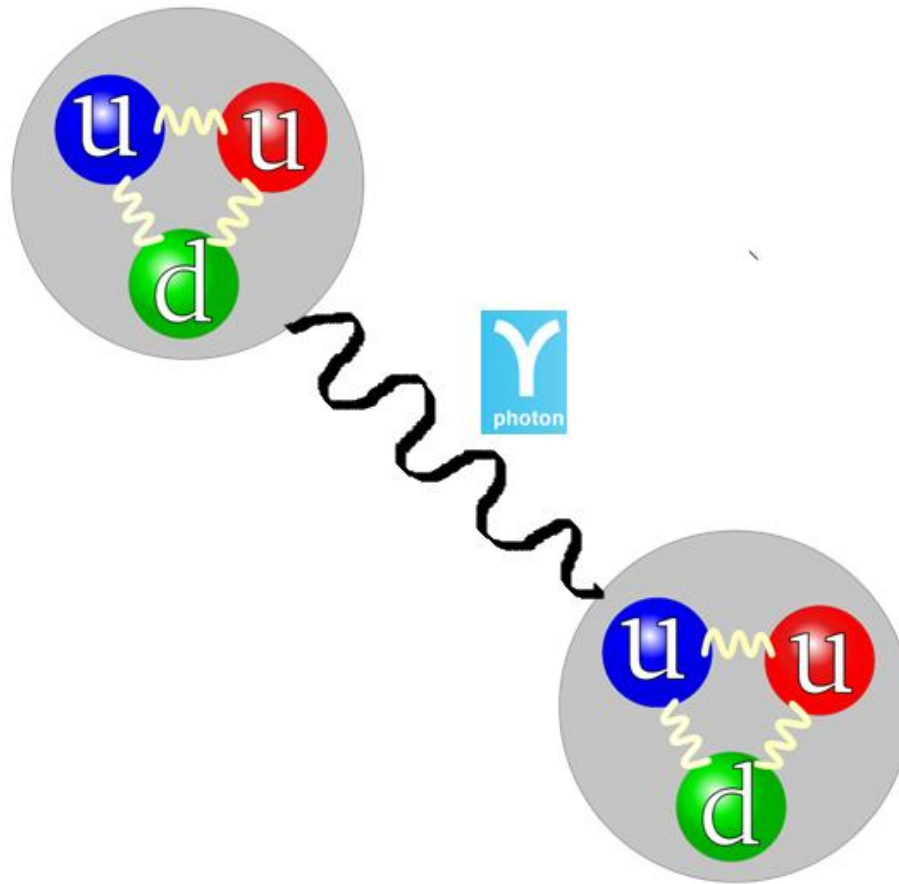
$$\begin{aligned}
\mathcal{L}_{SM} = & -\frac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc} \partial_\mu g_\nu^a g_\mu^b g_\nu^c - \frac{1}{4}g_s^2 f^{abc} f^{ade} g_\mu^b g_\nu^c g_\mu^d g_\nu^e - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- - \\
& M^2 W_\mu^+ W_\mu^- - \frac{1}{2}\partial_\nu 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_\nu W_\mu^- - W_\nu^- \partial_\nu 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 \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{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}{}_{\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}{}_{\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_\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^\lambda}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \frac{ig}{2} \frac{m_\nu^\lambda}{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_\nu^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \\
& \frac{g}{2} \frac{m_\nu^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_\nu^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) - \frac{ig}{2} \frac{m_\nu^\lambda}{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}$$

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- **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, ...

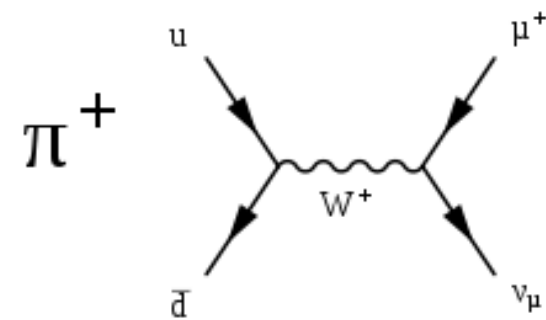
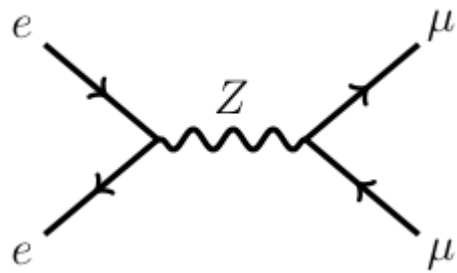
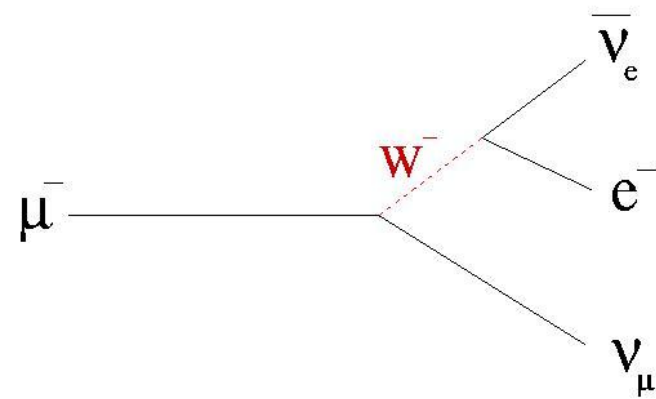
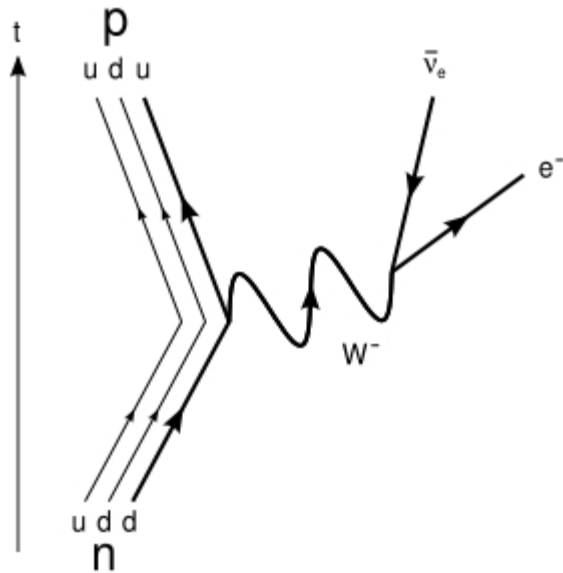
## Electromagnetism.

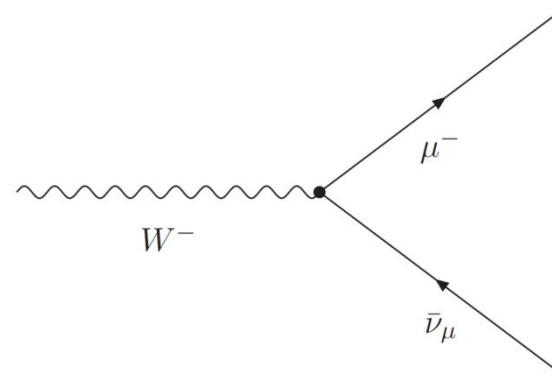
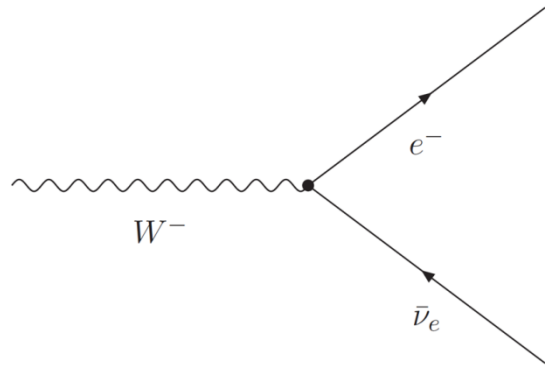
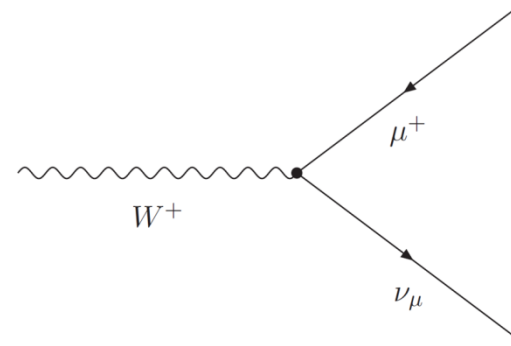
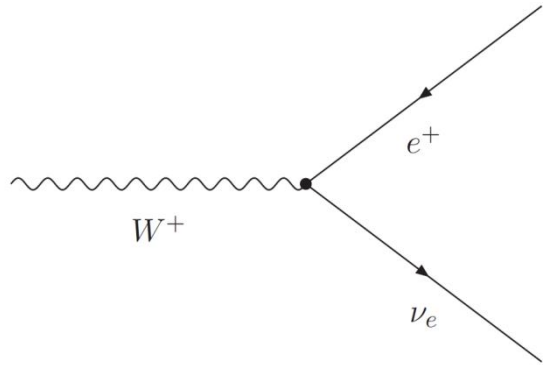
- \* Interactions between charged particles (quarks and charged leptons).
- \* Mediated by massless photons (spin one).



## Weak interaction.

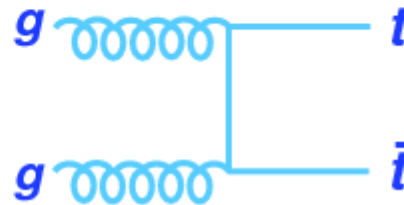
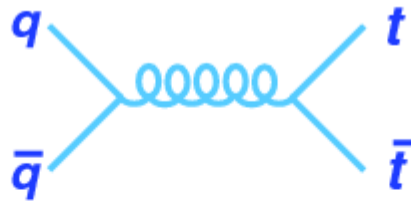
- \* Interactions between the left-handed components of the fermions.
- \* Mediated by massive weak bosons  $W$  and  $Z$ .
- \* Self interactions between  $W$  and  $Z$  bosons

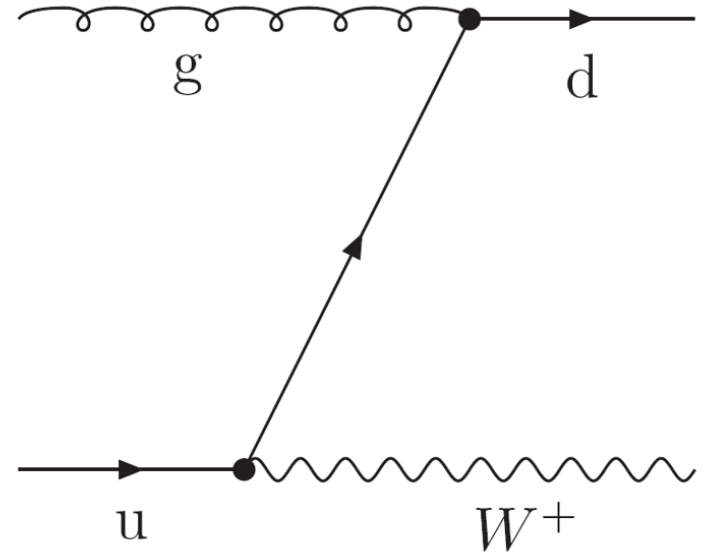
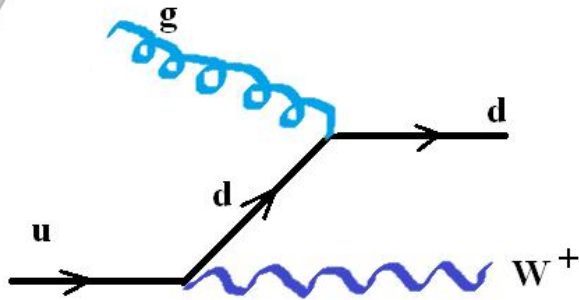
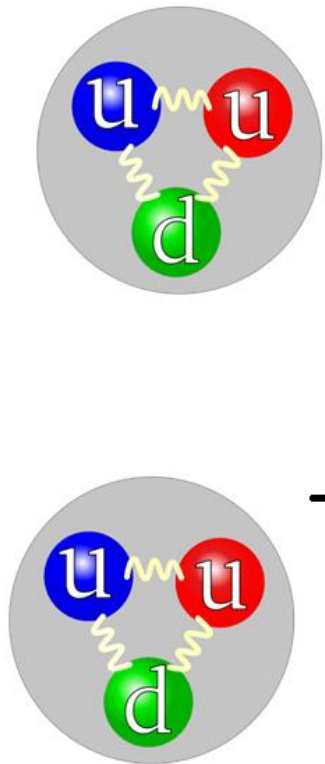


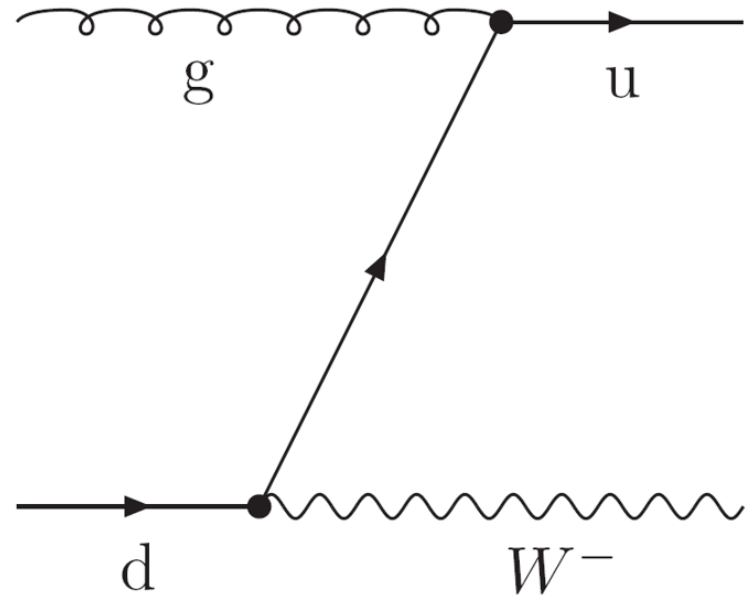
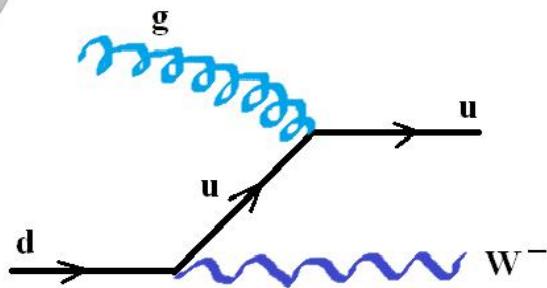
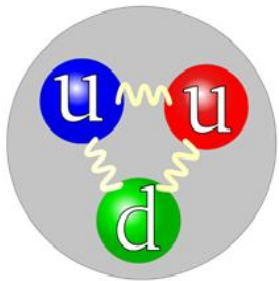
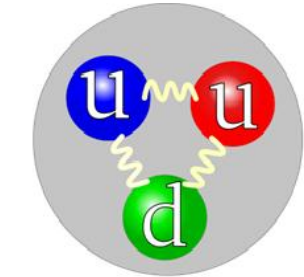


## Strong interactions.

- \* 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.

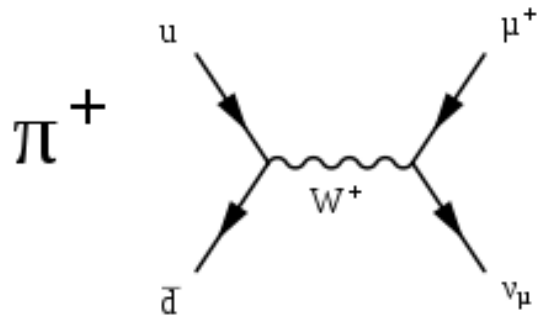
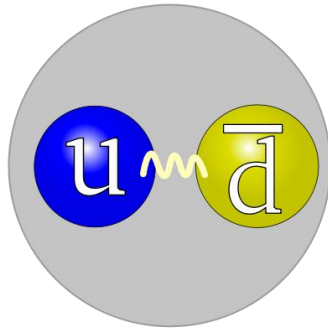




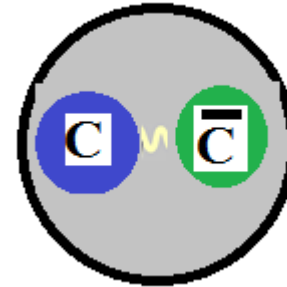




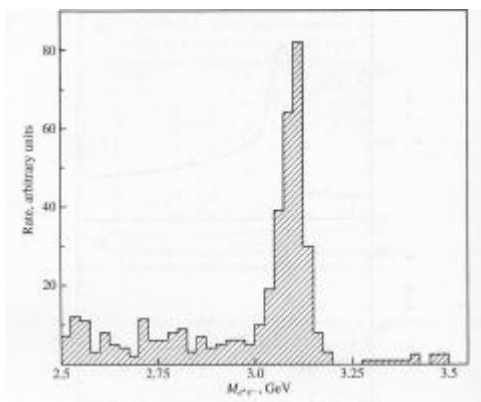
## Pion



## Charmonium The $J/\psi$ meson



$J/\psi$  is a bound state of charm-anticharm,



⇐ **Discovery 1:** Ting's group

$$pN \rightarrow e^+e^- X$$

at  $P_{\text{lab}} = 30 \text{ GeV}/c$

[Aubert et al., PRL, 6/11/1974]

$\sigma, \text{nb}$

Found a peak in  $e^+e^-$  inv.mass at 3.1 GeV, called it  $J$

**Discovery 2:** Richter's group ⇒

(a)  $e^+e^- \rightarrow \text{hadrons}$

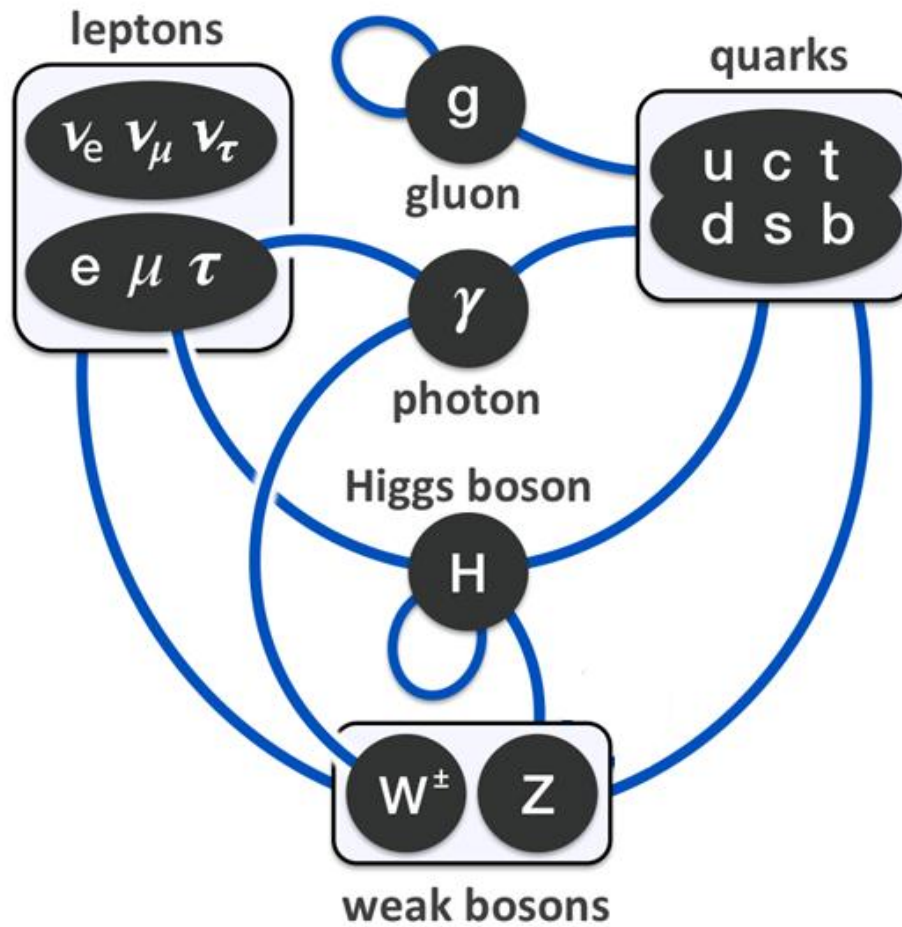
(b)  $e^+e^- \rightarrow \mu^+\mu^-$

(c)  $e^+e^- \rightarrow e^+e^-$

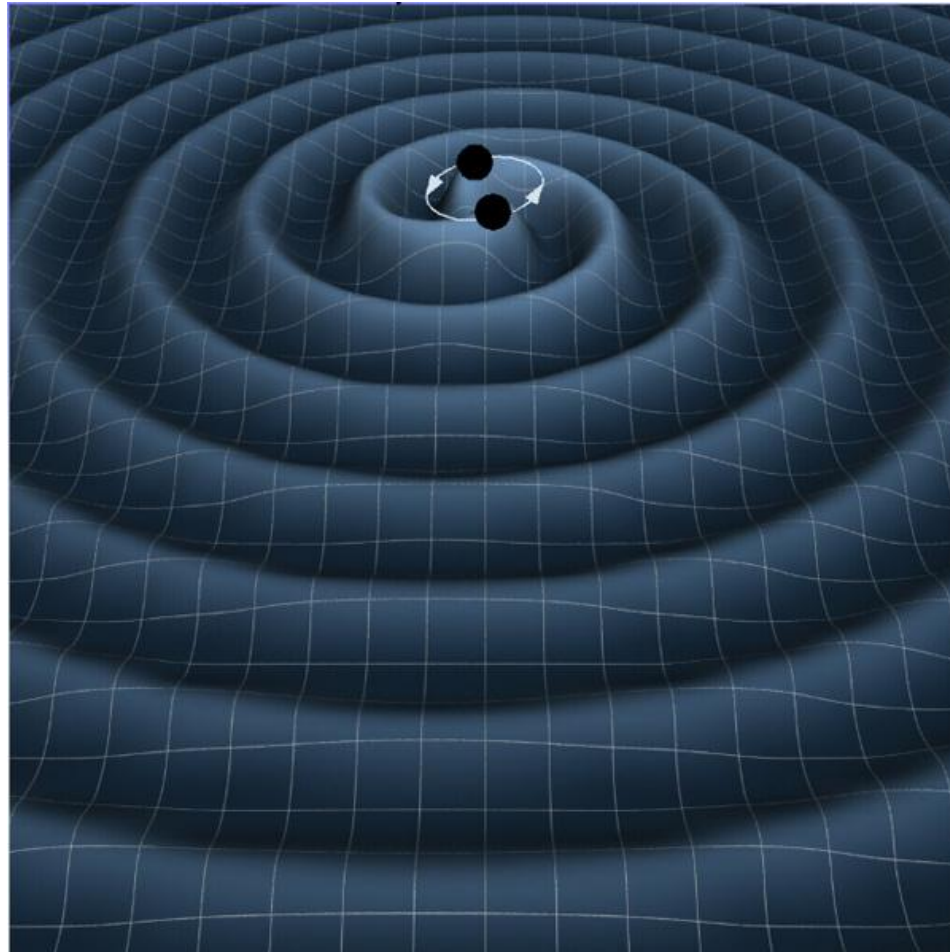
[Augustin et al., PRL, 7/11/1974]

Found a peak in all these three cross-sections,

at the c.m.s. energy 3.1 GeV; called it  $\psi$ .



# Gravity



the **graviton** - a hypothetical elementary particle that mediates the force of gravitation

	$\nu_e$	$\nu_\mu$	$\nu_\tau$
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

	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

	e electron	$\mu$ muon	$\tau$ 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

	d down	s strange	b bottom
Mass	4.8 MeV	95 MeV	4.2 GeV
Charge	-1/3	-1/3	-1/3
Spin	1/2	1/2	1/2
Discovered	1968 SLAC	1947(1964) Manchester University	1977 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

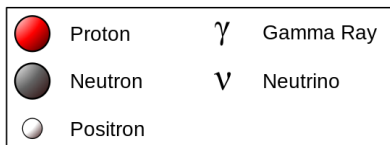
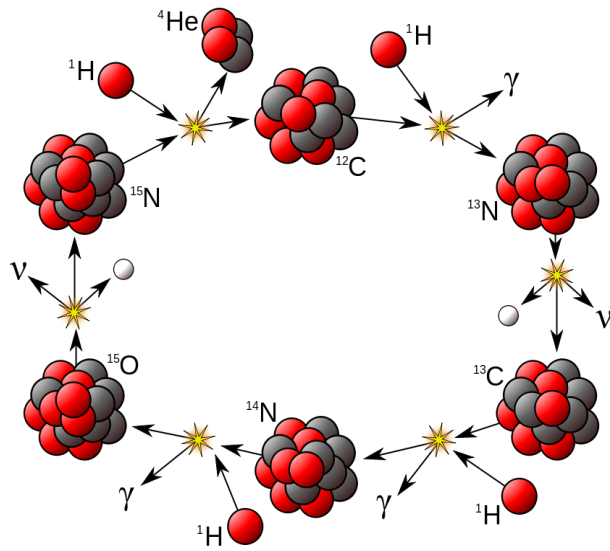
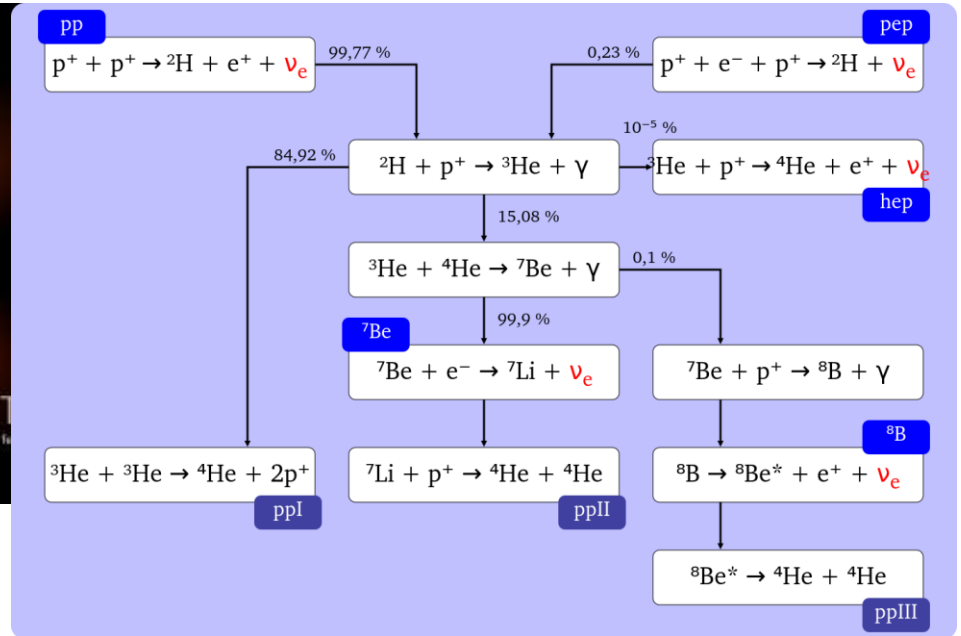
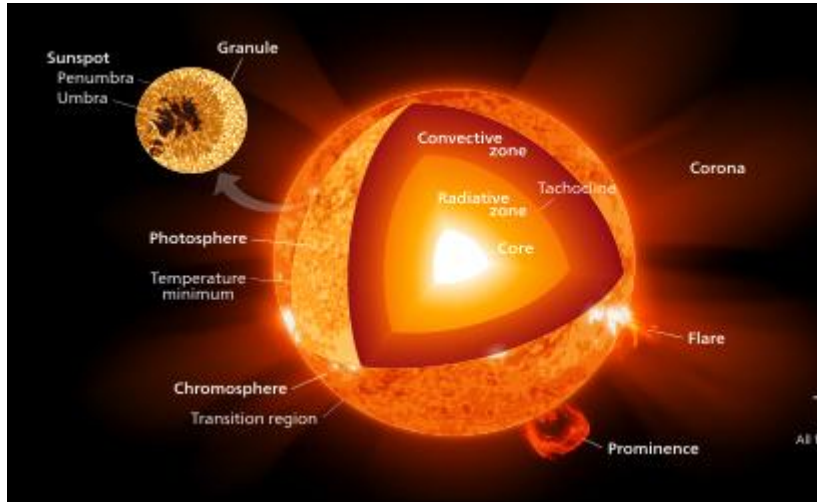
## Spin:

1

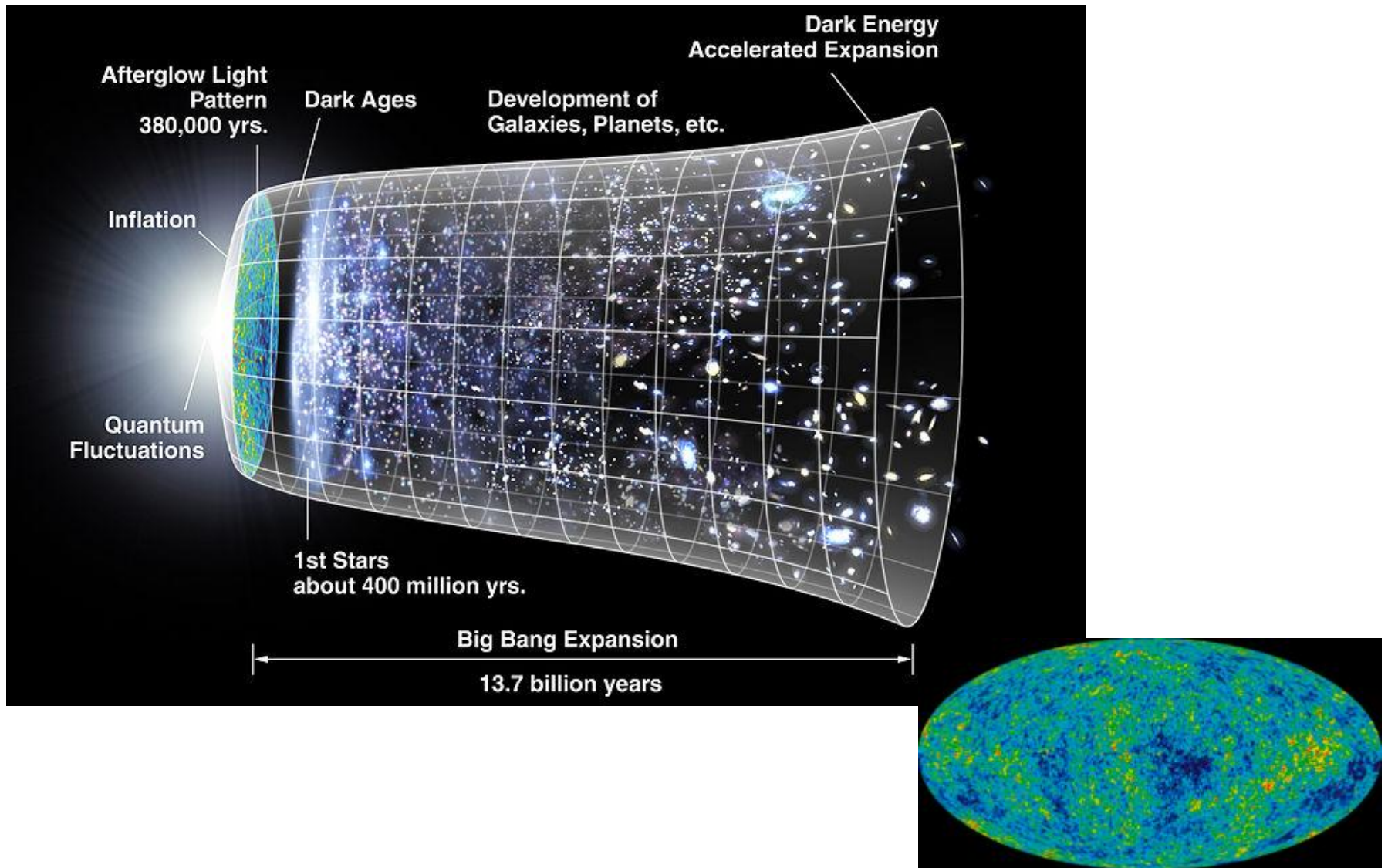
## About:

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



# 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

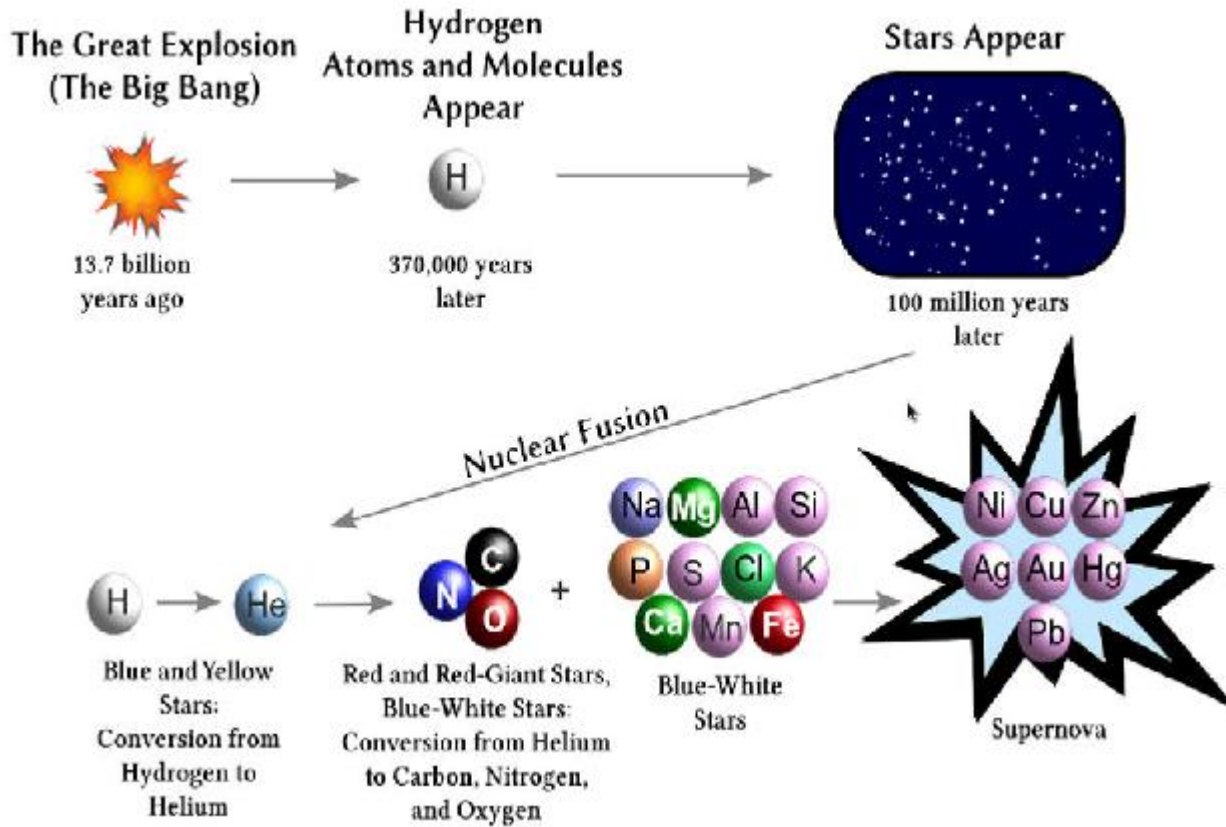
Gas clouds collapse. The fusion of stars begins.

## 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