Neutrino Physics

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Outline

- Brief overview of particle physics
- Properties of neutrino
- Production of neutrino
- Detection of neutrino
- Massive neutrinos

References

- ***Spaceship Neutrino***, by C. Sutton, Cambridge University Press, 1992.

  A popular science book on the history of neutrino.

- ***Nuclear and Particle Physics: An Introduction***, by B.R. Martin, Wiley, 2006.

  A textbook for undergraduate students.

- ***Elementary Particles and Their Interactions: Concepts and Phenomena***, by H.K. Quang and X.Y. Pham, Springer, 2005.

  A textbook on particle physics for advanced undergraduate and graduate students.

- ***Current Aspects of Neutrino Physics***, ed. D. Caldwell, Springer, 2001.

  A reference overviewing the field of neutrino physics for researchers.

- ***Physics of Massive Neutrinos, 2nd.ed.***, by F. Boehm and P. Vogel, Cambridge University Press, 2003.

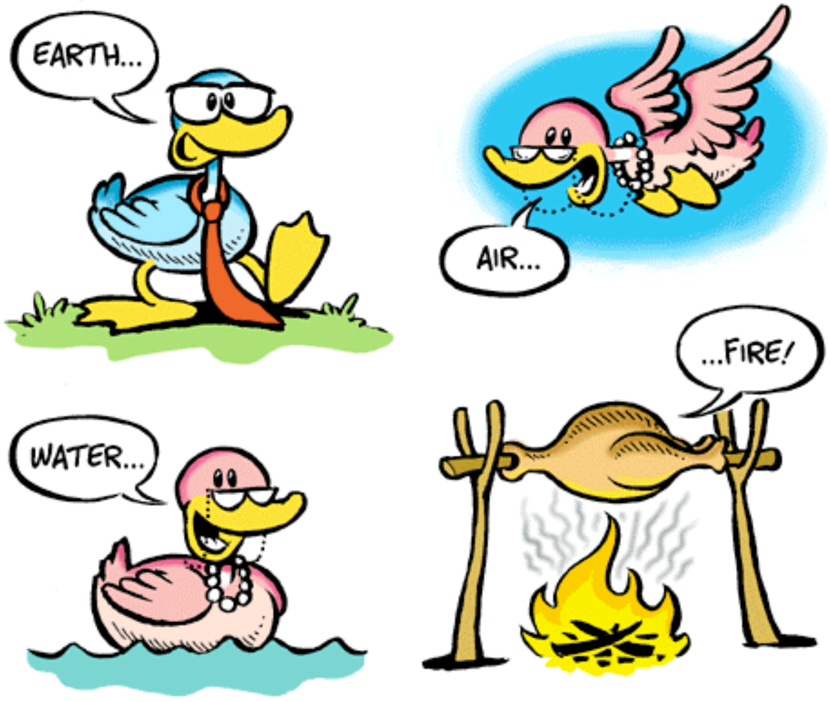
  A reference on neutrino physics for researchers.

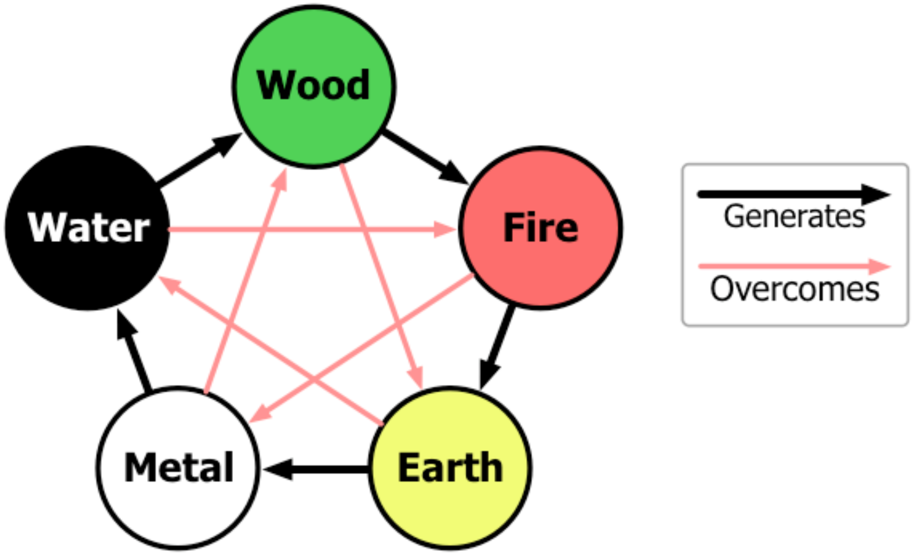
A Quick Tour of Particle Physics

What Are The Basic Building Blocks?

- Ancient ideas:

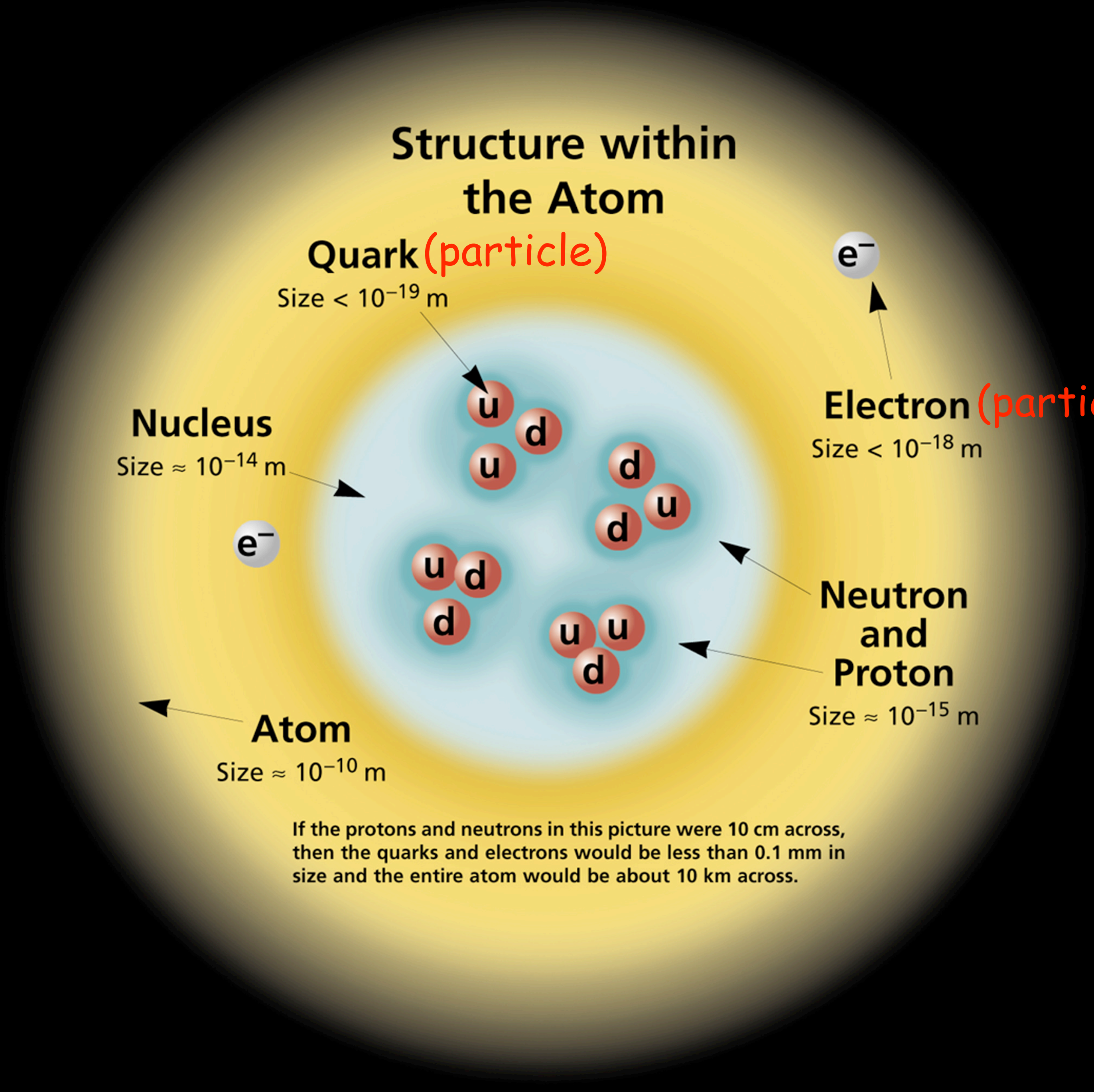
Greek (Aristotle)





Chinese

Structure within the Atom



Quark (particle)

Size $< 10^{-19}$ m

Electron (particle)

Size $< 10^{-18}$ m

Nucleus

Size $\approx 10^{-14}$ m

Neutron and Proton

Size $\approx 10^{-15}$ m

Atom

Size $\approx 10^{-10}$ m

If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

Current Basic Building Blocks of Matter

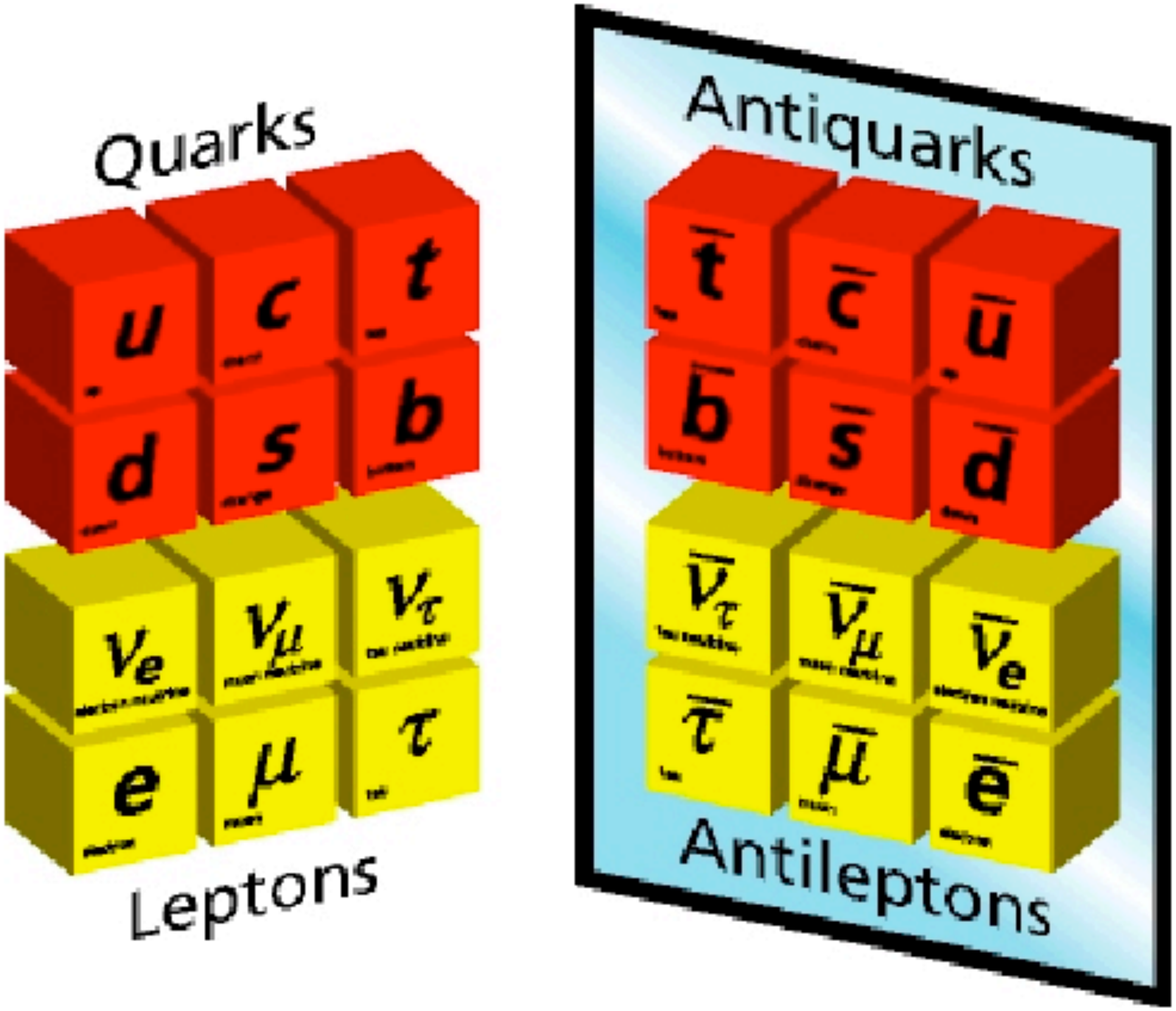
Electric charge
in unit of |e|:

2/3

-1/3

0

-1



-2/3

1/3

0

1

- *A particle and its antiparticle have the same mass*
- *All quarks and leptons are spin-1/2 particles*

Some Units And Convention

- Unit of energy used in nuclear and particle physics:

electron volt (eV)

1 eV = energy gained by a particle of charge |e| after accelerated through a potential difference of 1 V
= $(1.6 \times 10^{-19}\ C) \times 1\ V$
= 1.6×10^{-19} J

$$1\,keV = 10^{3}\,eV$$
$$1\,MeV = 10^{6}\,eV$$
$$1\,GeV = 10^{9}\,eV$$
$$1\,TeV = 10^{12}\,eV$$

- We often take energy units as mass units:

$E = mc^2$; $c = 1$

$\Rightarrow 1\ eV/c^2 \equiv 1\ eV = 1.8 \times 10^{-36}$ kg

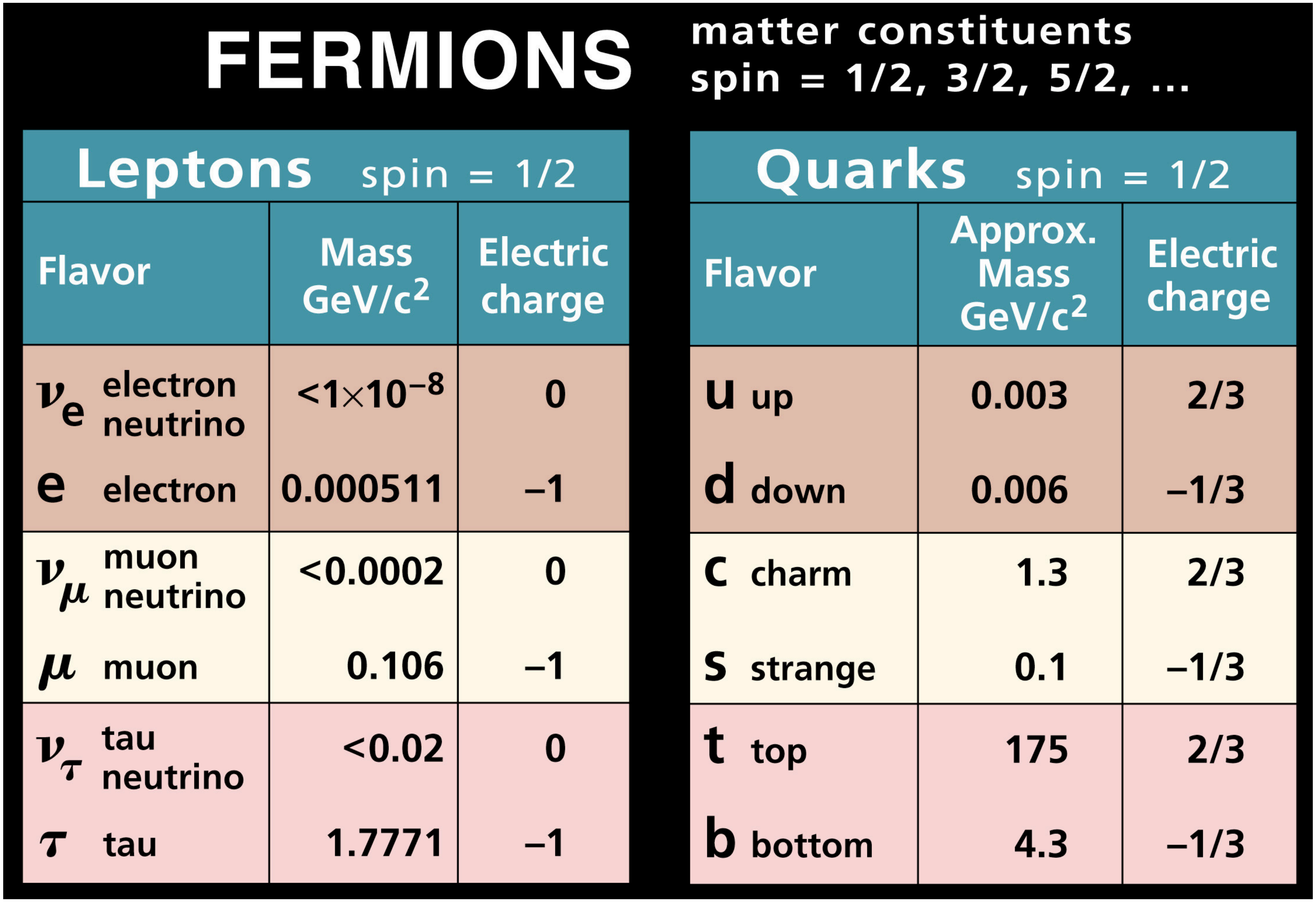
- Relation between energy and distance:

Planck constant, $h = 6.63 \times 10^{-34}$ J-s

Reduced Planck constant, $\hbar = \frac{h}{2\pi} = 1.05 \times 10^{-34}\ \mathrm{J\text{-}s}$

$$\hbar c \equiv \hbar = 197 \times 10^{-15}\,\mathrm{MeV \cdot m} = 197\ \mathrm{MeV \cdot fm}$$

Quarks And Leptons



FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

Quarks spin = 1/2

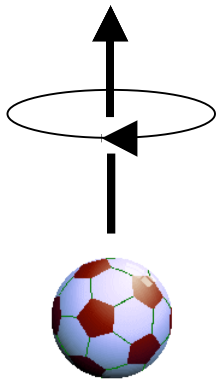
Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3

Spin

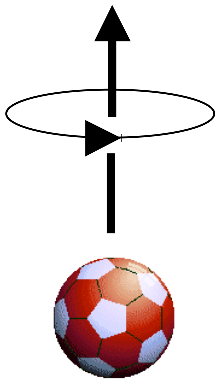
- A kind of angular momentum
- Fermions: 1/2, 3/2, …

  Bosons: 0, 1, …

Spin $\frac{1}{2}$

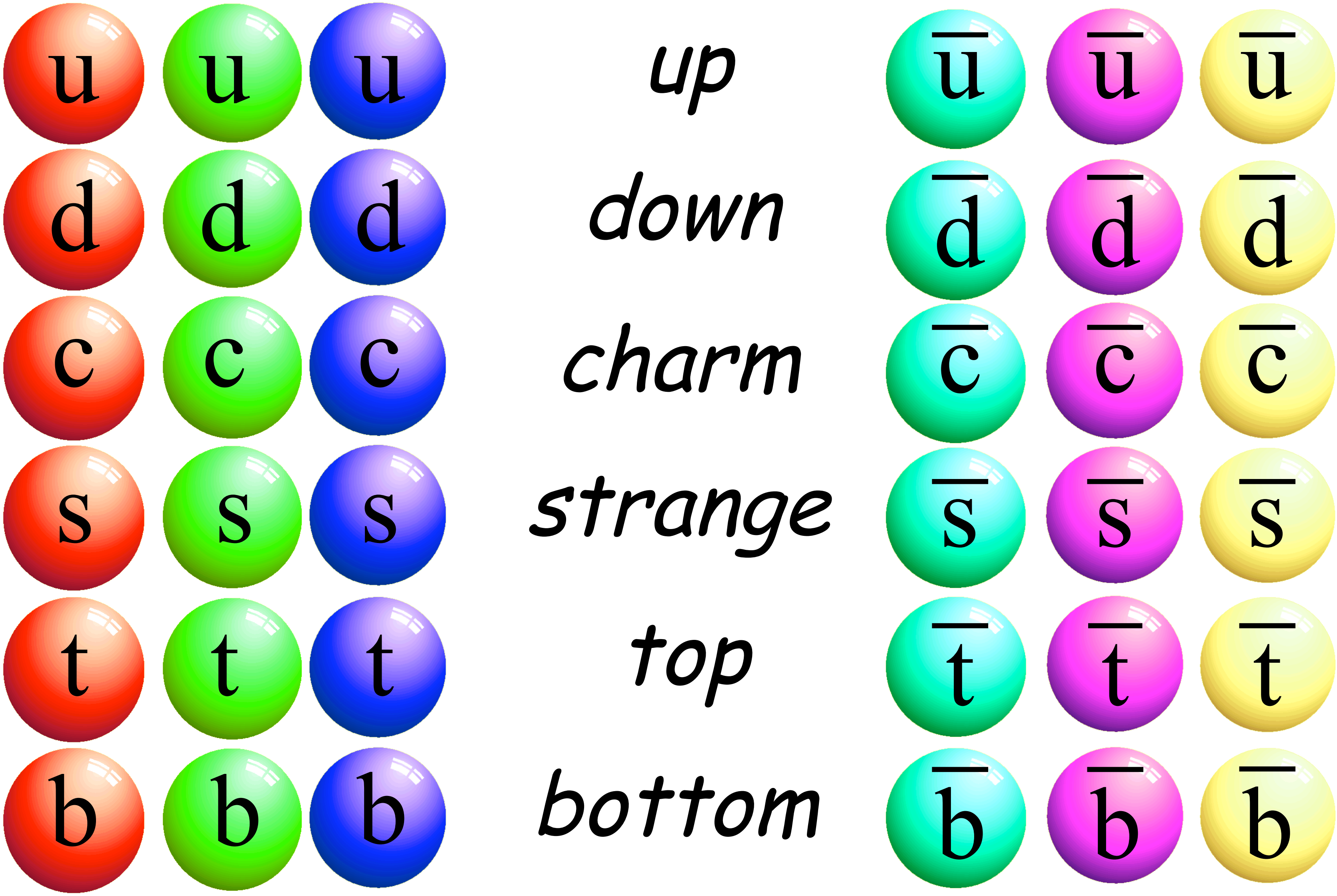


Left-handed state



Right-handed state

Quarks Carry Colour



quarks				Antiquarks		
u	u	u	*up*	$\bar{u}$	$\bar{u}$	$\bar{u}$
d	d	d	*down*	$\bar{d}$	$\bar{d}$	$\bar{d}$
c	c	c	*charm*	$\bar{c}$	$\bar{c}$	$\bar{c}$
s	s	s	*strange*	$\bar{s}$	$\bar{s}$	$\bar{s}$
t	t	t	*top*	$\bar{t}$	$\bar{t}$	$\bar{t}$
b	b	b	*bottom*	$\bar{b}$	$\bar{b}$	$\bar{b}$

Hadrons: Strongly Interacting Particles

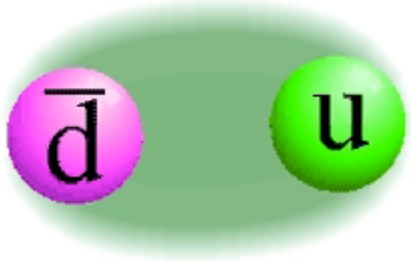
Baryons:

Proton

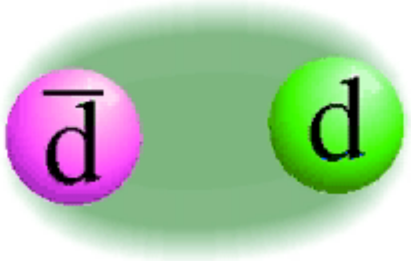
Λ

Antiproton

Mesons:



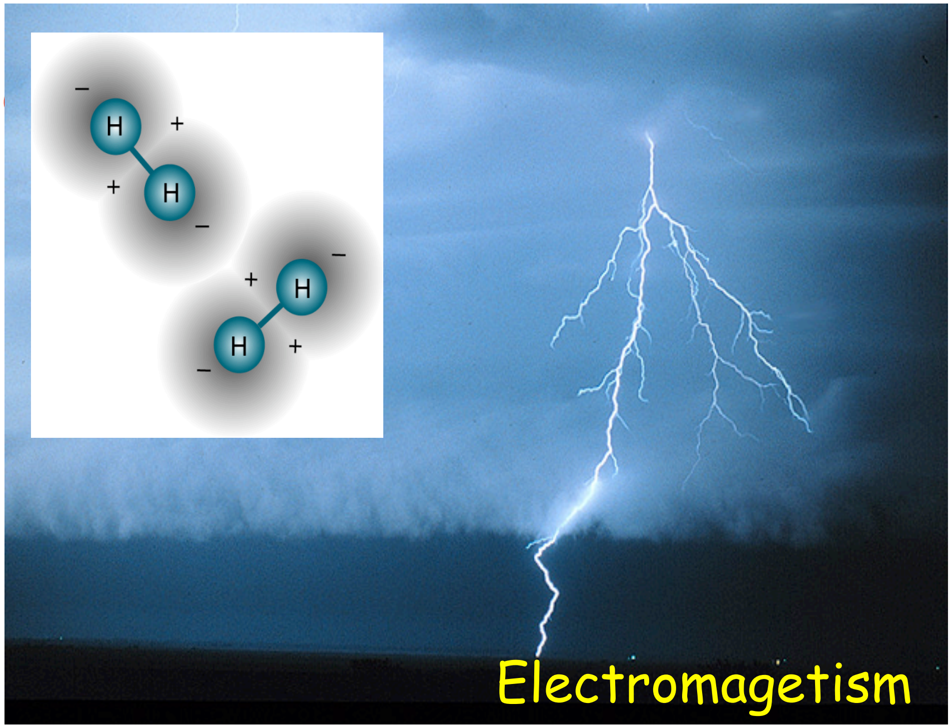
π^+



π^0

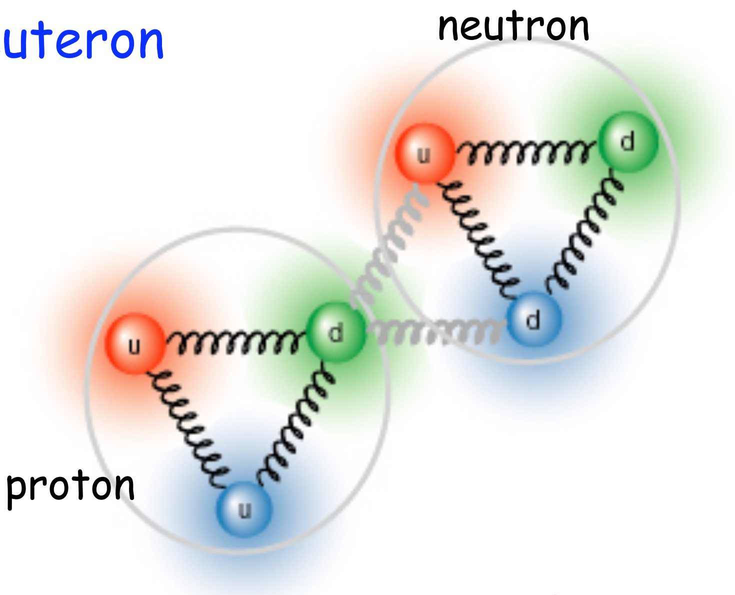
Hadrons are colourless !

Gravitation



Electromagetism

deuteron



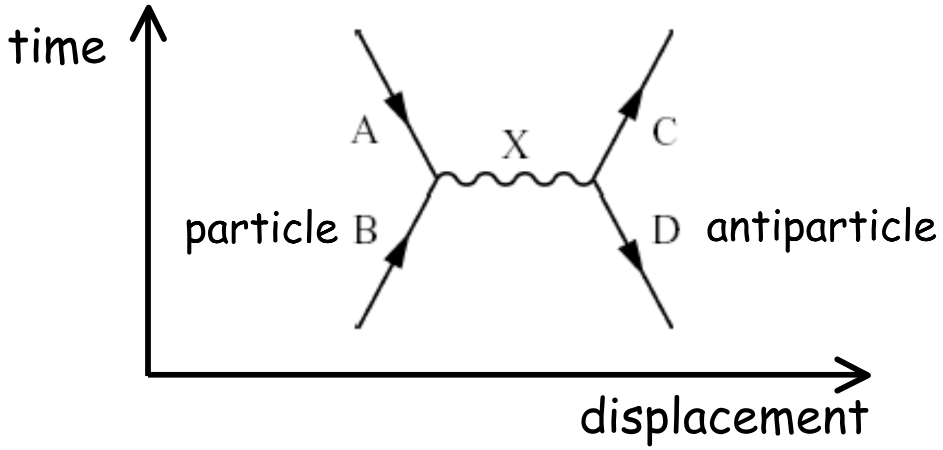
Strong

$^{212}\text{Po} \rightarrow {}^{208}\text{Pb} + \alpha(8.95\ \text{MeV})$

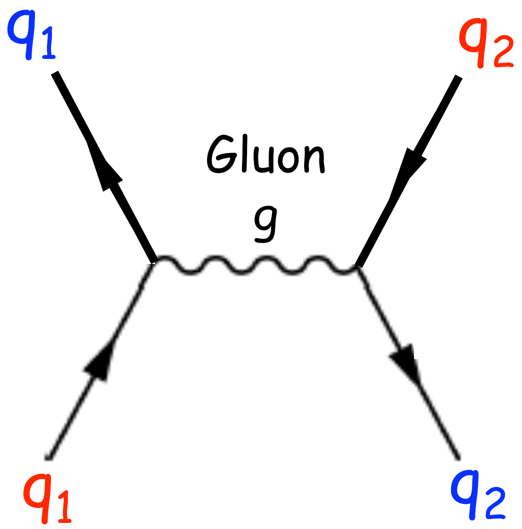
Weak

Interactions of Particles

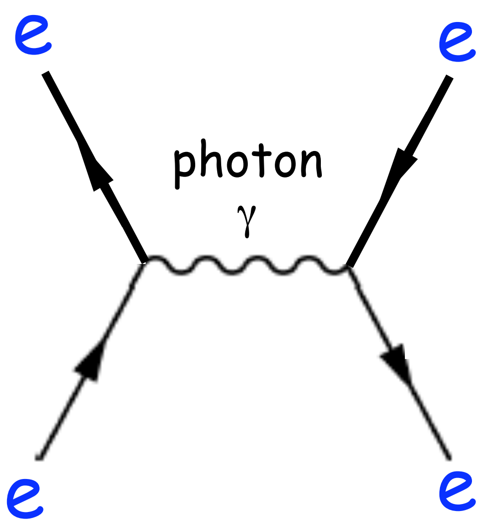
Feynman diagram:



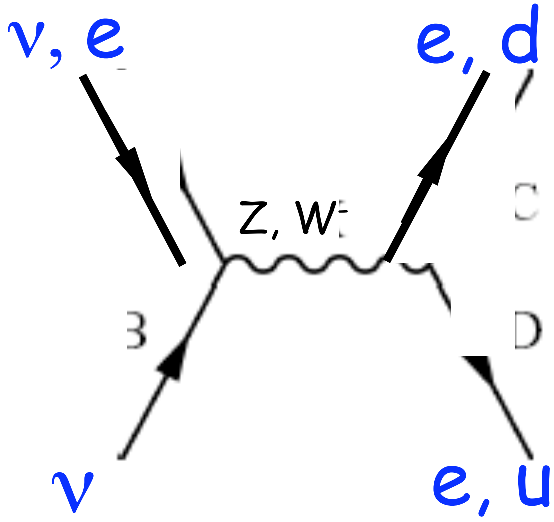
Strong



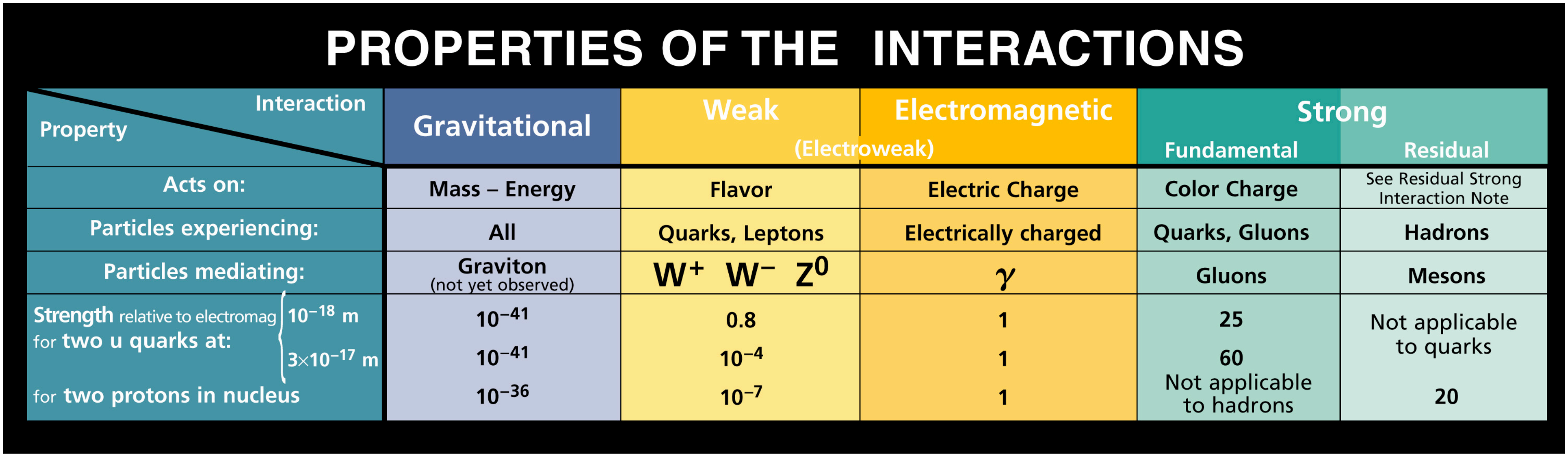
Electromagnetic



Weak



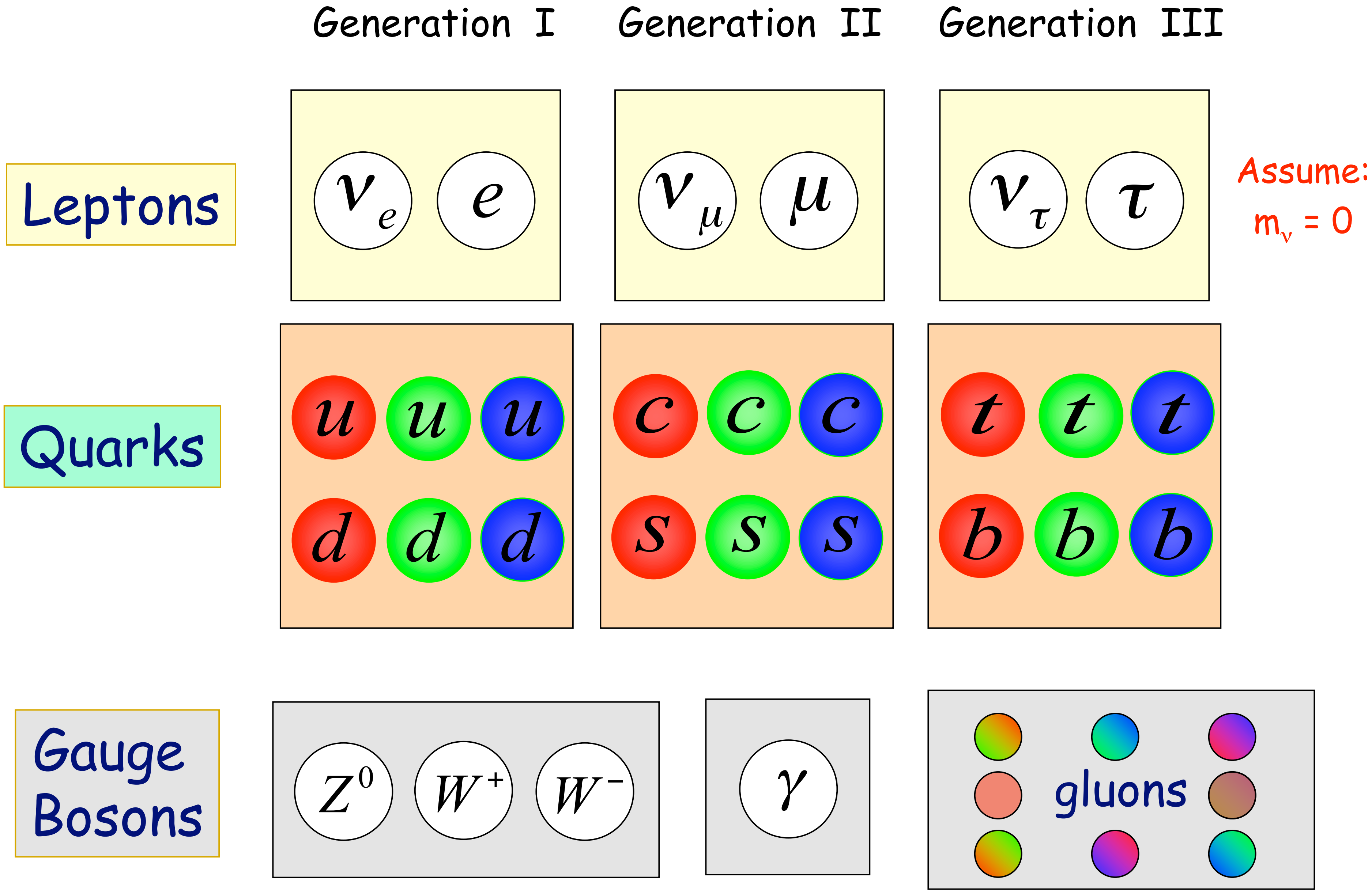
Summary of Force Carriers



PROPERTIES OF THE INTERACTIONS

Interaction Property		Gravitational	Weak	Electromagnetic	Strong	
			(Electroweak)		Fundamental	Residual
Acts on:		Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:		All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:		Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for **two u quarks at:**	10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
	3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for **two protons in nucleus**		10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Standard Model



Generation I Generation II Generation III

Leptons

ν_e e

ν_μ μ

ν_τ τ

Assume:
$m_\nu = 0$

Quarks

u u u
d d d

c c c
s s s

t t t
b b b

Gauge Bosons

Z^0 W^+ W^-

γ

gluons

Lepton Numbers

- Base on observations, in the Standard Model, :

$L_e = 1$ for e^- , ν_e such that $\Delta L_e = 0$
$L_\mu = 1$ for μ^- , ν_μ such that $\Delta L_\mu = 0$
$L_\tau = 1$ for τ^- , ν_τ such that $\Delta L_\tau = 0$

e.g. tau lepton decay:

$$\tau^- \rightarrow \mu^- + \bar{\nu}_\mu + \nu_\tau$$

tau lepton number L_τ:	**+1**	**0**	**0**	**+1**
muon lepton number L_μ:	**0**	**+1**	**-1**	**0**

$$\tau^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\tau$$

tau lepton number L_τ:	**-1**	**0**	**0**	**-1**
electron lepton number L_e:	**0**	**-1**	**+1**	**0**

Baryon number

- Observation: proton is stable !
  proton lifetime, $\tau_p > 10^{31}$ years
- Why $p \not\rightarrow e^+ + \pi^0$??

Introduce a quantum number in the Standard Model:

	quarks	antiquarks
Baryon number, B:	+1/3	-1/3

such that

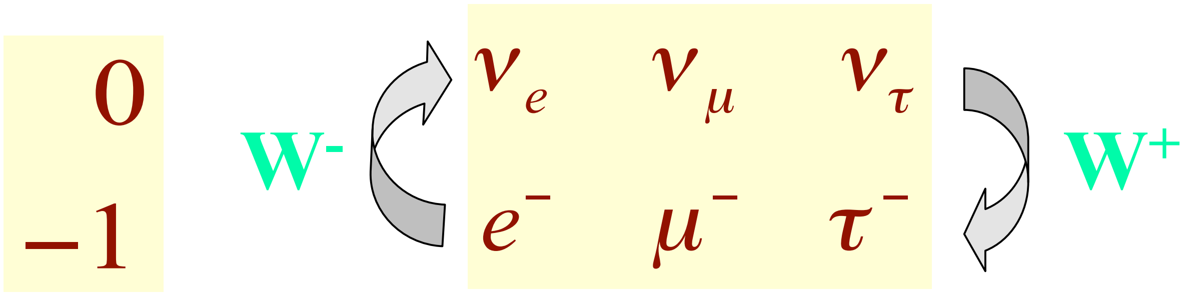
All baryons have B = 1
All mesons have B = 0
In any process $\Delta B = 0$

$$p \rightarrow e^+ + \pi^0$$

B: 1 0 $\Delta B \neq 0$

Weak interactions

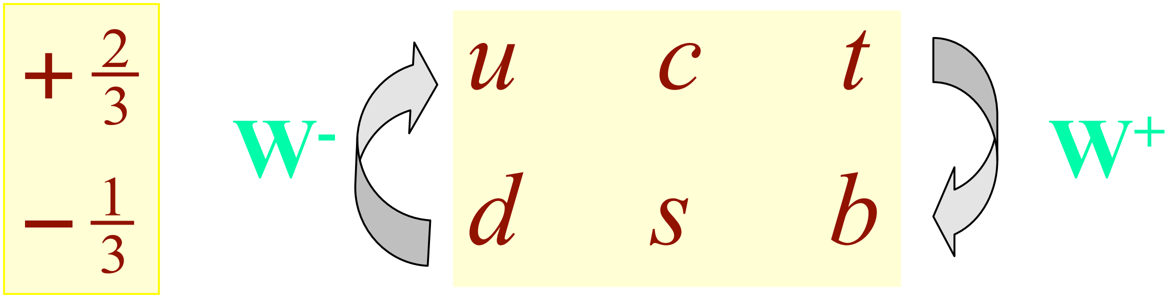
- Leptons:



$$\begin{array}{c} 0 \\ -1 \end{array} \quad W^- \quad \begin{array}{ccc} \nu_e & \nu_\mu & \nu_\tau \\ e^- & \mu^- & \tau^- \end{array} \quad W^+$$

W bosons transform leptons INSIDE the same generation

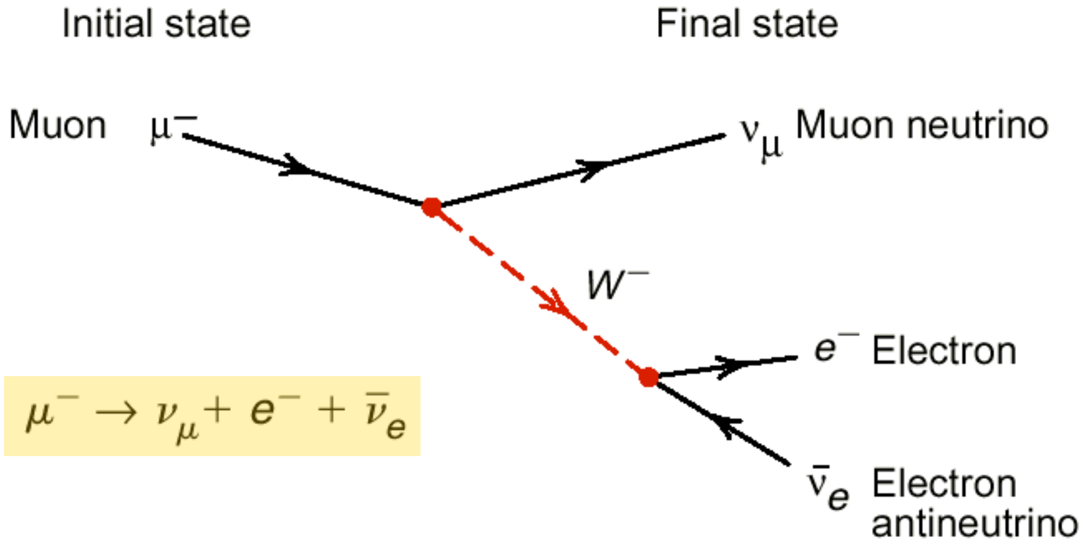
- Quarks:



$$\begin{array}{c} +\frac{2}{3} \\ -\frac{1}{3} \end{array} \quad W^- \quad \begin{array}{ccc} u & c & t \\ d & s & b \end{array} \quad W^+$$

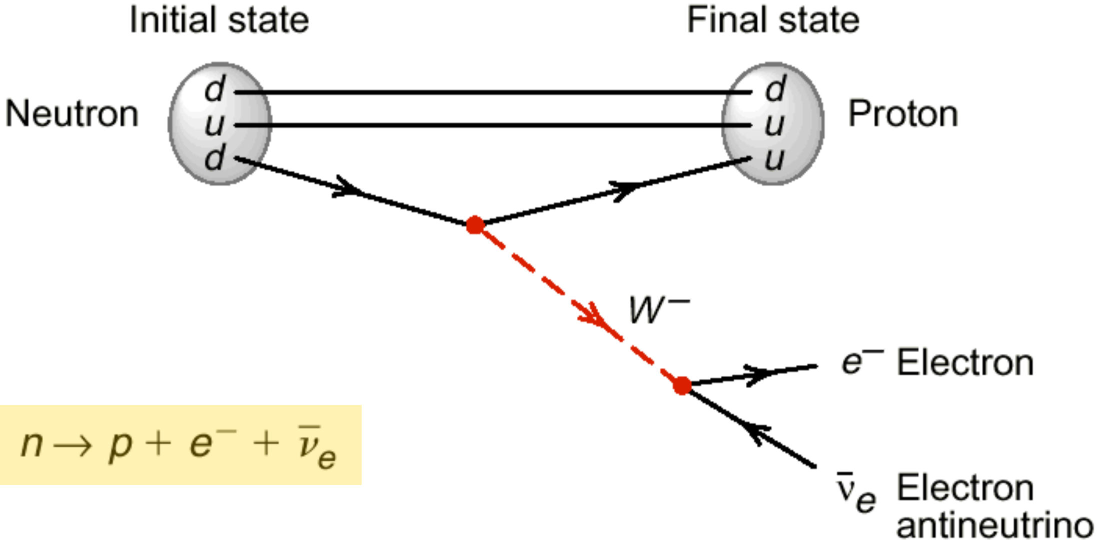
Some Weak Decays

Leptonic decay:



$$\mu^- \rightarrow \nu_\mu + e^- + \bar{\nu}_e$$

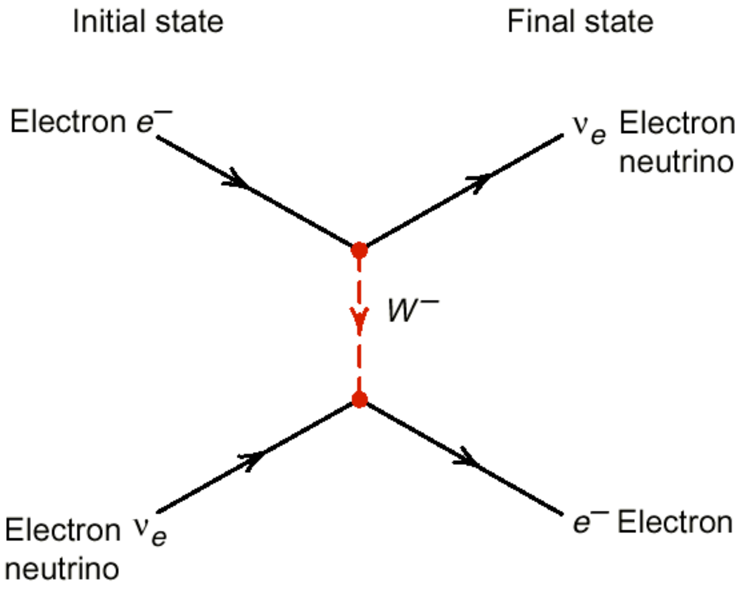
Semileptonic decay:



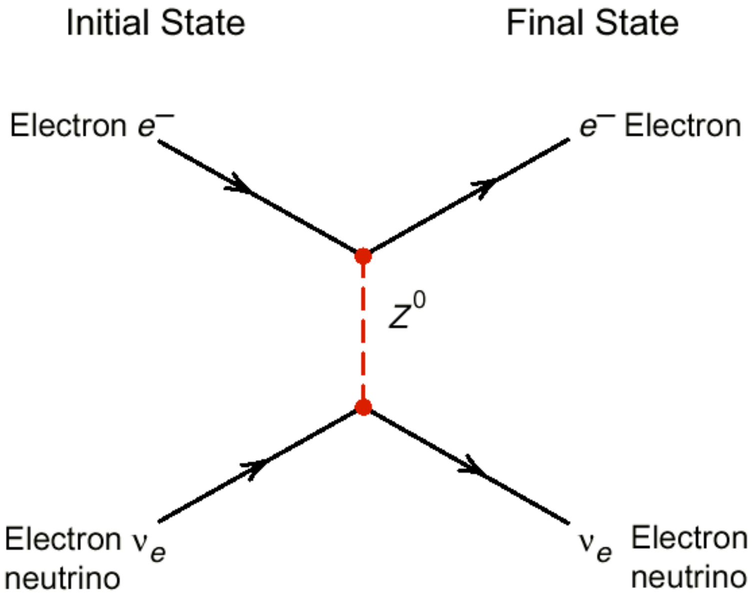
$$n \rightarrow p + e^- + \bar{\nu}_e$$

Weak Interactions: CC and NC processes

- Charged Current (CC):
  - "Charged-Current" reaction: exchange of W boson
  - Proposed by Fermi (1934)
  - Responsible for neutron β decay
  - Incoming neutrino needs enough energy to produce the outgoing lepton

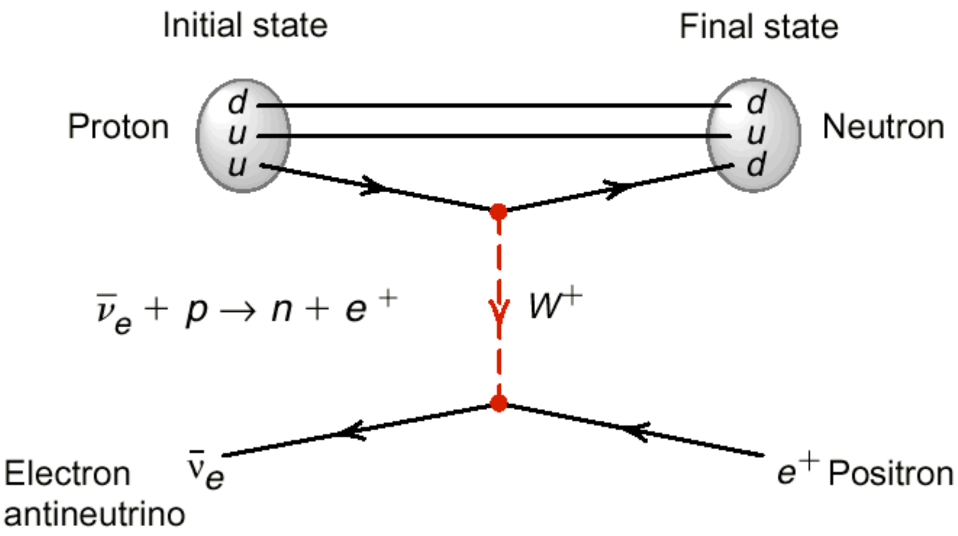


- Neutral Current (NC):
  - "Neutral Current" reaction: exchange of Z boson
  - Proposed by Weinberg-Salam
  - Discovered with neutrinos
  - Can occur for all flavours

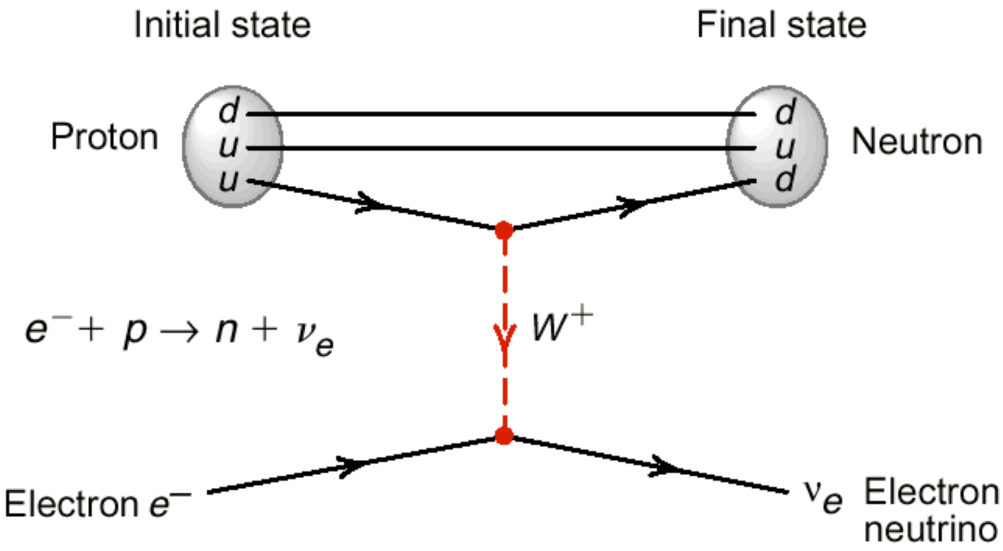


Some Weak Reactions Involving Neutrinos

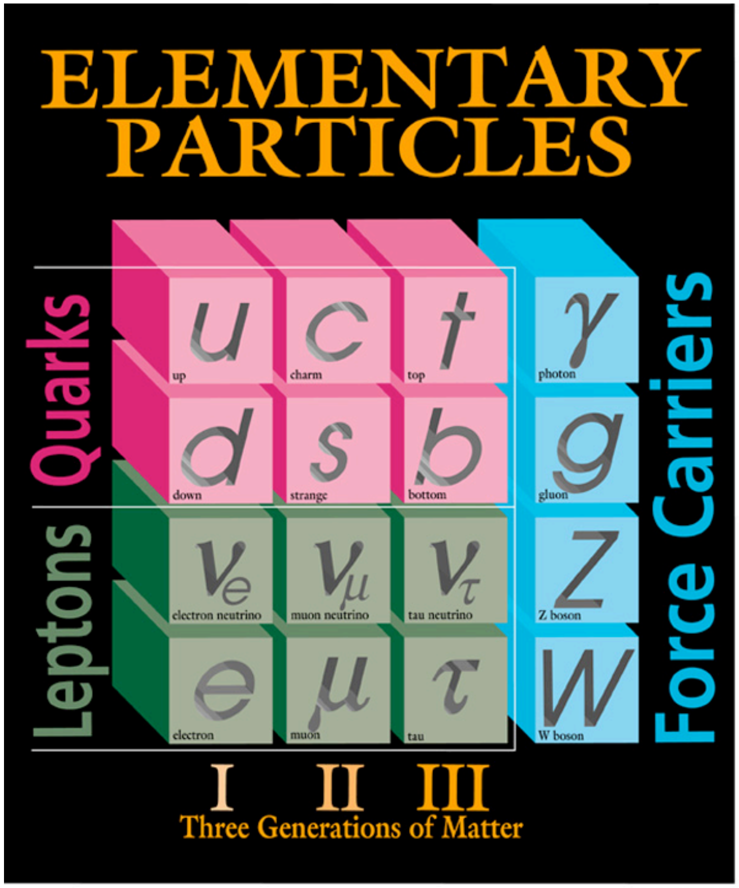
Inverse beta-decay:



Electron capture:



Summary



Fermilab 95-759

- The Standard Model accounts all the elementary particles known today.
- Interactions of quarks and leptons are identical
- However, studies of the neutrinos indicate the Standard Model is incomplete