




e μ and τ

$\approx 0.511 \text{ MeV}/c^2$ -1 $\frac{1}{2}$  electron	$\approx 105.66 \text{ MeV}/c^2$ -1 $\frac{1}{2}$  muon	$\approx 1.7768 \text{ GeV}/c^2$ -1 $\frac{1}{2}$  tau
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Andy "Dijon" French
March 2024

Tune based upon *Don't stop me now* by Queen.
Lyrics and arrangement by AF

three generations of matter (fermions)

I

II

III

mass
charge
spin

$\approx 2.2 \text{ MeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$
u
up

$\approx 1.28 \text{ GeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$
c
charm

$\approx 173.1 \text{ GeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$
t
top

$\approx 4.7 \text{ MeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$
d
down

$\approx 96 \text{ MeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$
s
strange

$\approx 4.18 \text{ GeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$
b
bottom

$\approx 0.511 \text{ MeV}/c^2$
 -1
 $\frac{1}{2}$
e
electron

$\approx 105.66 \text{ MeV}/c^2$
 -1
 $\frac{1}{2}$
 μ
muon

$\approx 1.7768 \text{ GeV}/c^2$
 -1
 $\frac{1}{2}$
 τ
tau

$< 1.0 \text{ eV}/c^2$
 0
 $\frac{1}{2}$
 ν_e
electron neutrino

$< 0.17 \text{ MeV}/c^2$
 0
 $\frac{1}{2}$
 ν_μ
muon neutrino

$< 18.2 \text{ MeV}/c^2$
 0
 $\frac{1}{2}$
 ν_τ
tau neutrino

QUARKS

LEPTONS

(and their anti-particles!)

interactions / force carriers (bosons)

0
 0
 1
g
gluon

$\approx 125.11 \text{ GeV}/c^2$
 0
 0
H
higgs

0
 0
 1
 γ
photon

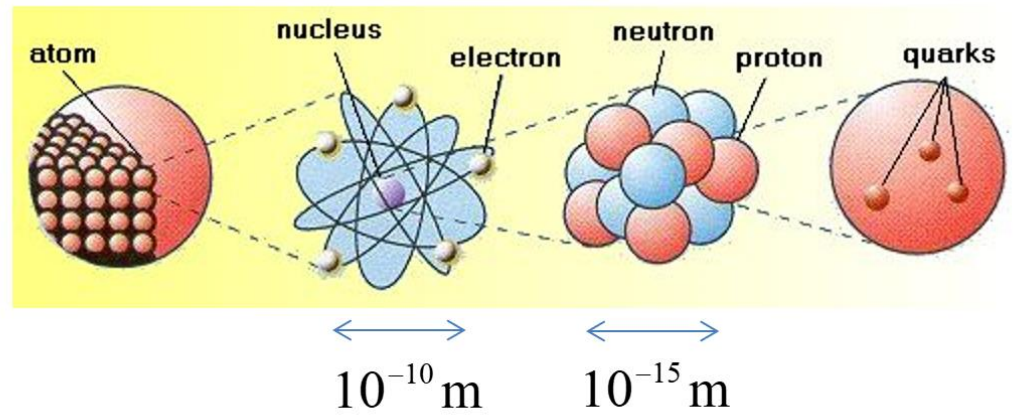
$\approx 91.19 \text{ GeV}/c^2$
 0
 1
Z
Z boson

$\approx 80.360 \text{ GeV}/c^2$
 ± 1
 1
W
W boson

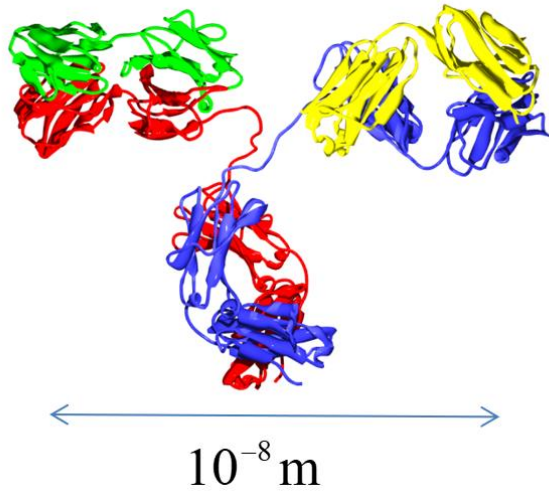
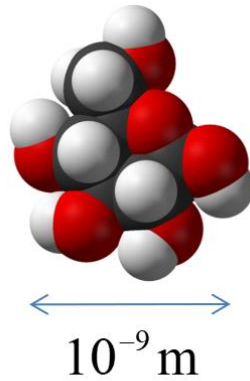
GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

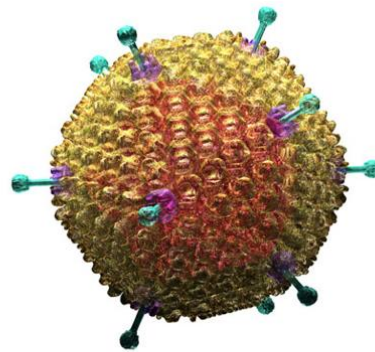
There are, two types of things



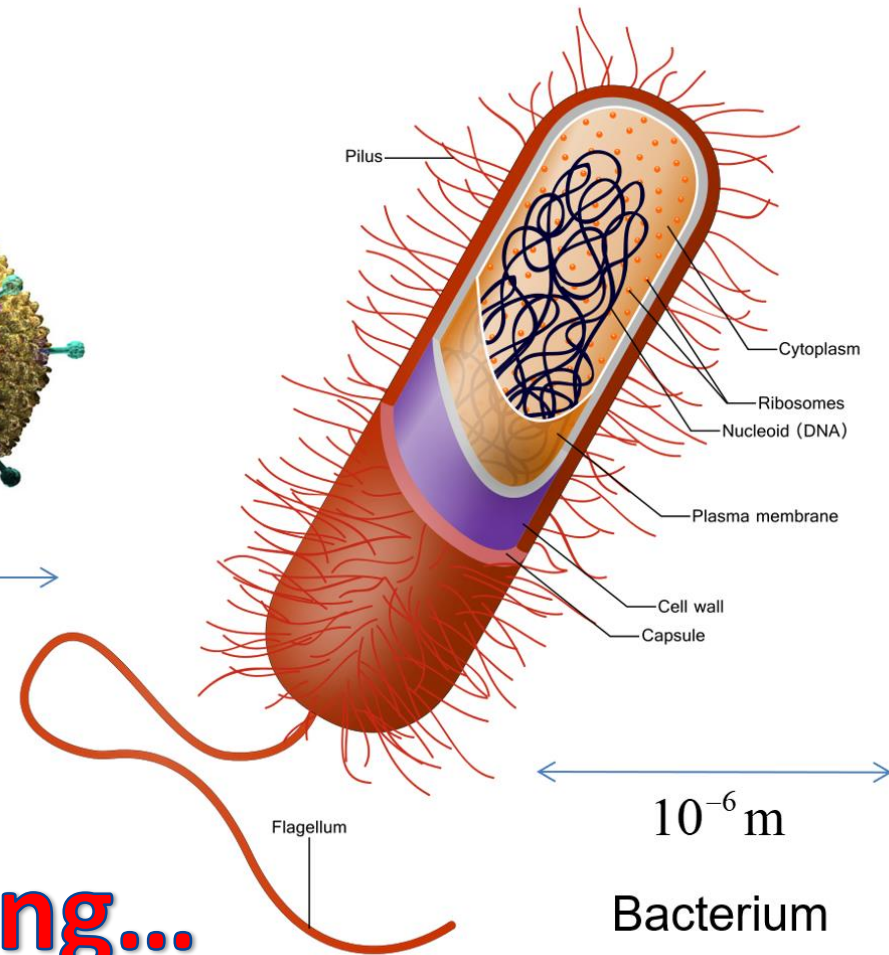
Glucose molecule



Antibody



Virus



Bacterium

That make everything...

A deep-field astronomical image showing a vast field of galaxies and stars against a black background. The galaxies are of various shapes and sizes, some appearing as bright, irregular patches of light, while others are more distant and faint. The stars are small, bright points of light, some with visible diffraction patterns. The overall scene is a dense, colorful mosaic of cosmic objects.

In the Universe

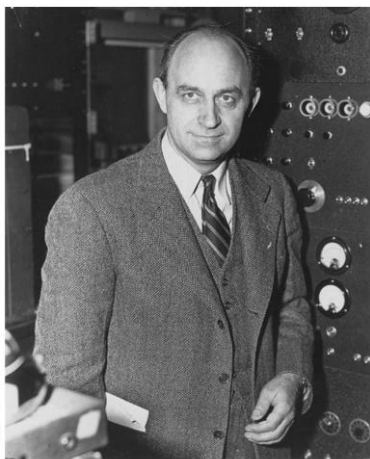
three generations of matter
(fermions)

	I	II	III
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	u up	c charm	t top
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
	d down	s strange	b bottom

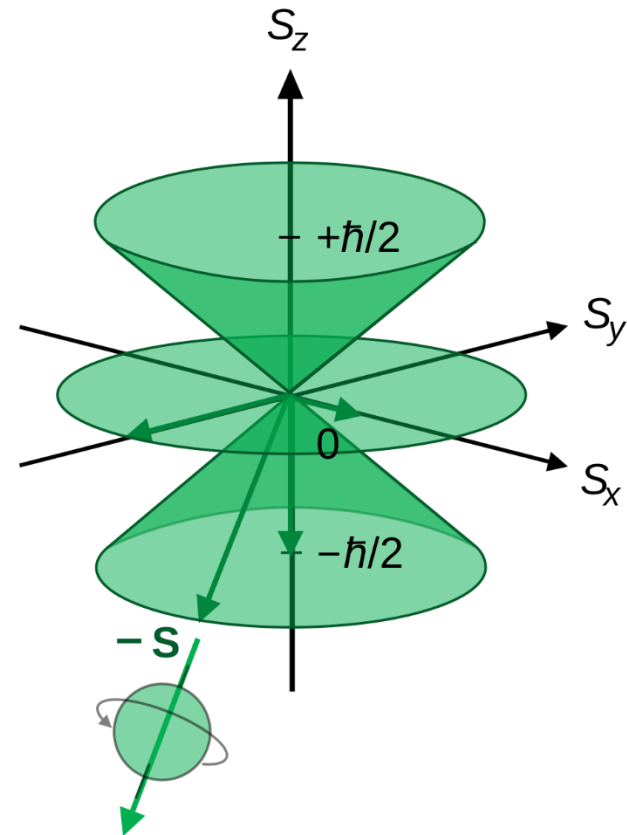
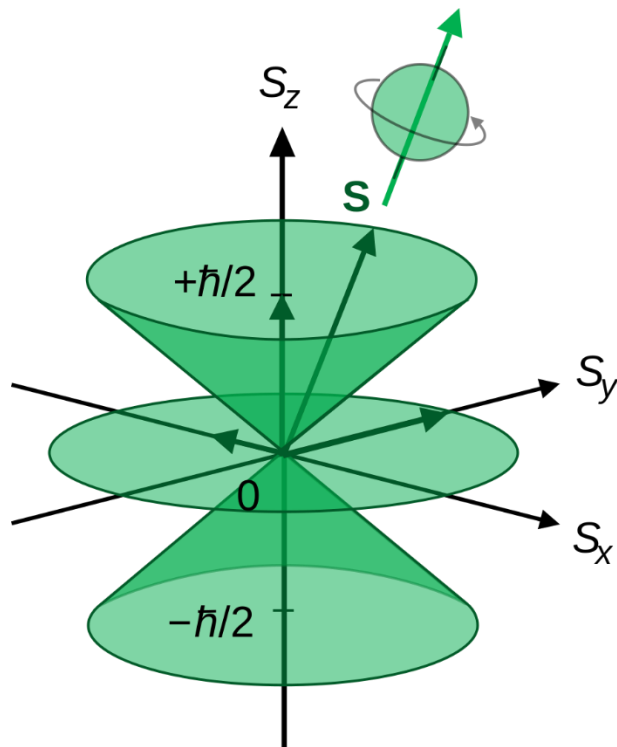
QUARKS

$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$
-1	-1	-1
$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
e electron	μ muon	τ tau
$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$
0	0	0
$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino

LEPTONS



Enrico Fermi
(1901-1954)



$$|\uparrow\rangle \equiv \left| +\frac{1}{2} \right\rangle$$

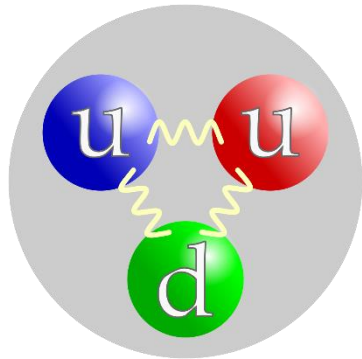
$$|\downarrow\rangle \equiv \left| -\frac{1}{2} \right\rangle$$

There's Fermions...
With half-integer spin yeah

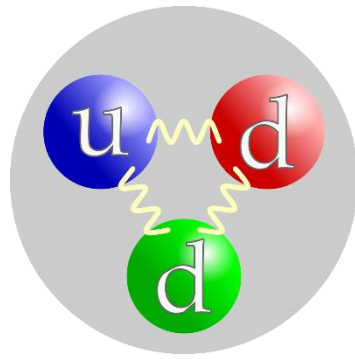
three generations of matter (fermions)

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charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
u	up	c	t
d	down	s	b
mass	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$
charge	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
u	up	c	t
d	down	s	b

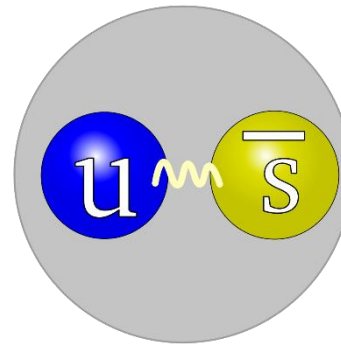
QUARKS



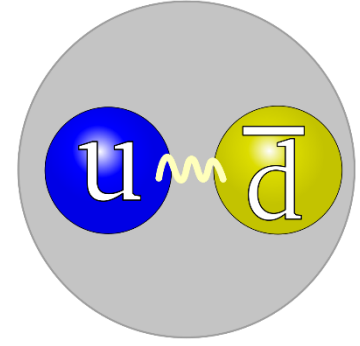
proton



neutron



kaon (+)



pion (+)

LEPTONS

$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$
-1	-1	-1
$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
e	μ	τ
electron	muon	tau
$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$
0	0	0
$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
ν_e	ν_μ	ν_τ
electron neutrino	muon neutrino	tau neutrino

**They're either
groupings of quarks, or leptons**

$\approx 0.511 \text{ MeV}/c^2$

-1

$\frac{1}{2}$



electron

$\approx 105.66 \text{ MeV}/c^2$

-1

$\frac{1}{2}$



muon

$\approx 1.7768 \text{ GeV}/c^2$

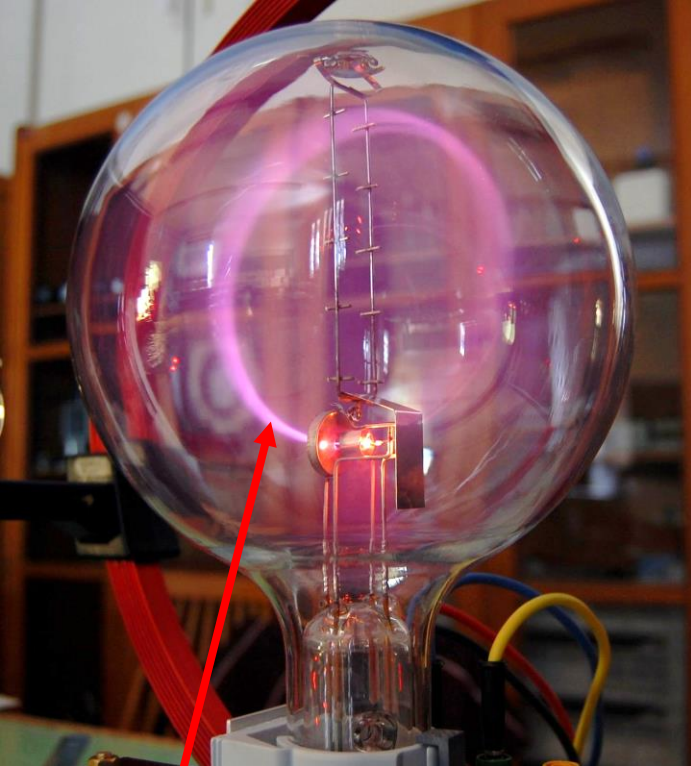
-1

$\frac{1}{2}$

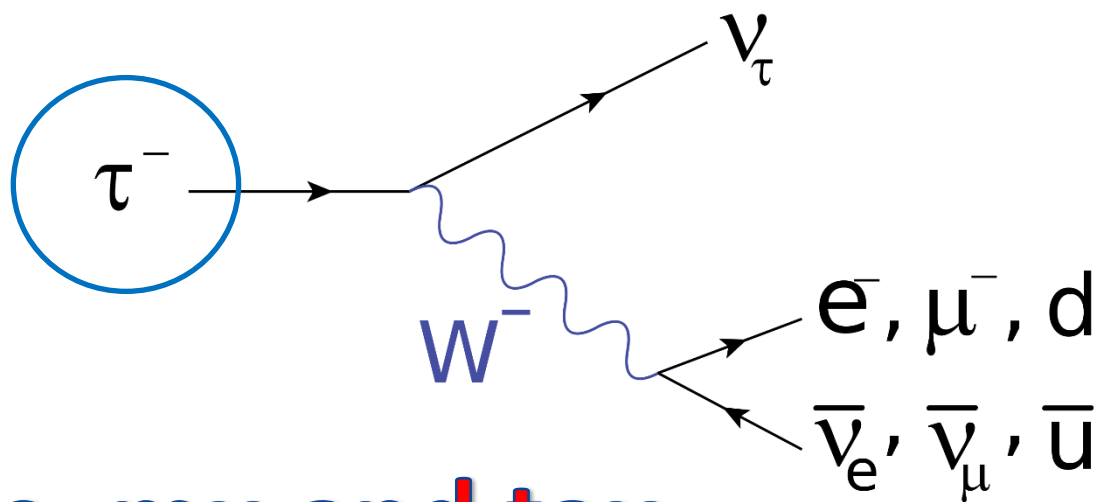
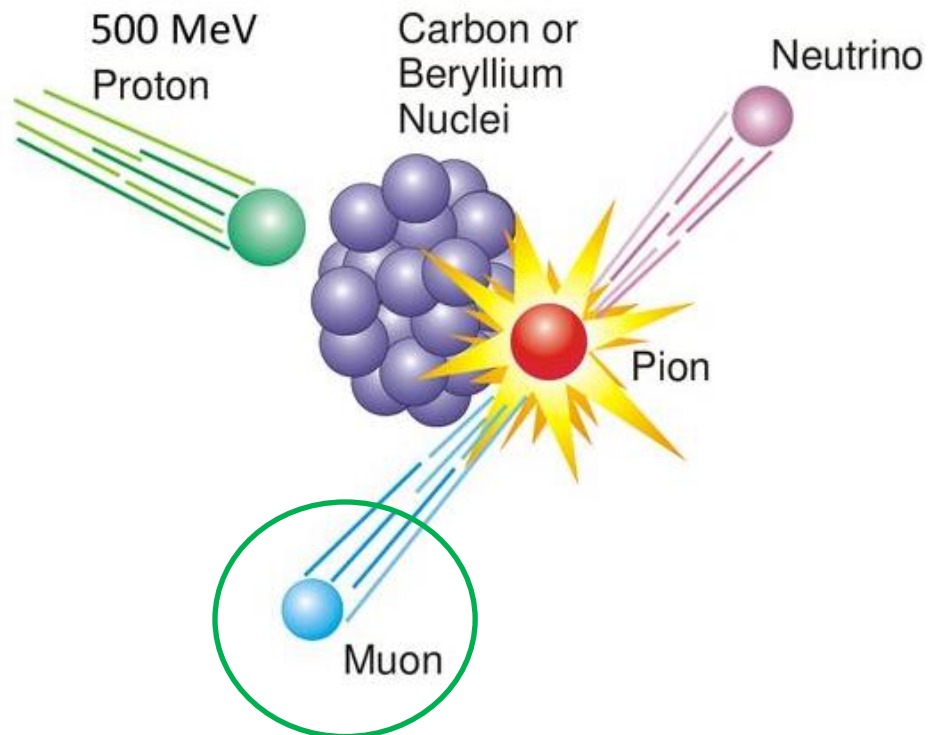


tau

(such as) e, mu and tau



e^-



e, mu and tau

$<1.0 \text{ eV}/c^2$

0
 $\frac{1}{2}$



**electron
neutrino**

$<0.17 \text{ MeV}/c^2$

0
 $\frac{1}{2}$



**muon
neutrino**

$<18.2 \text{ MeV}/c^2$

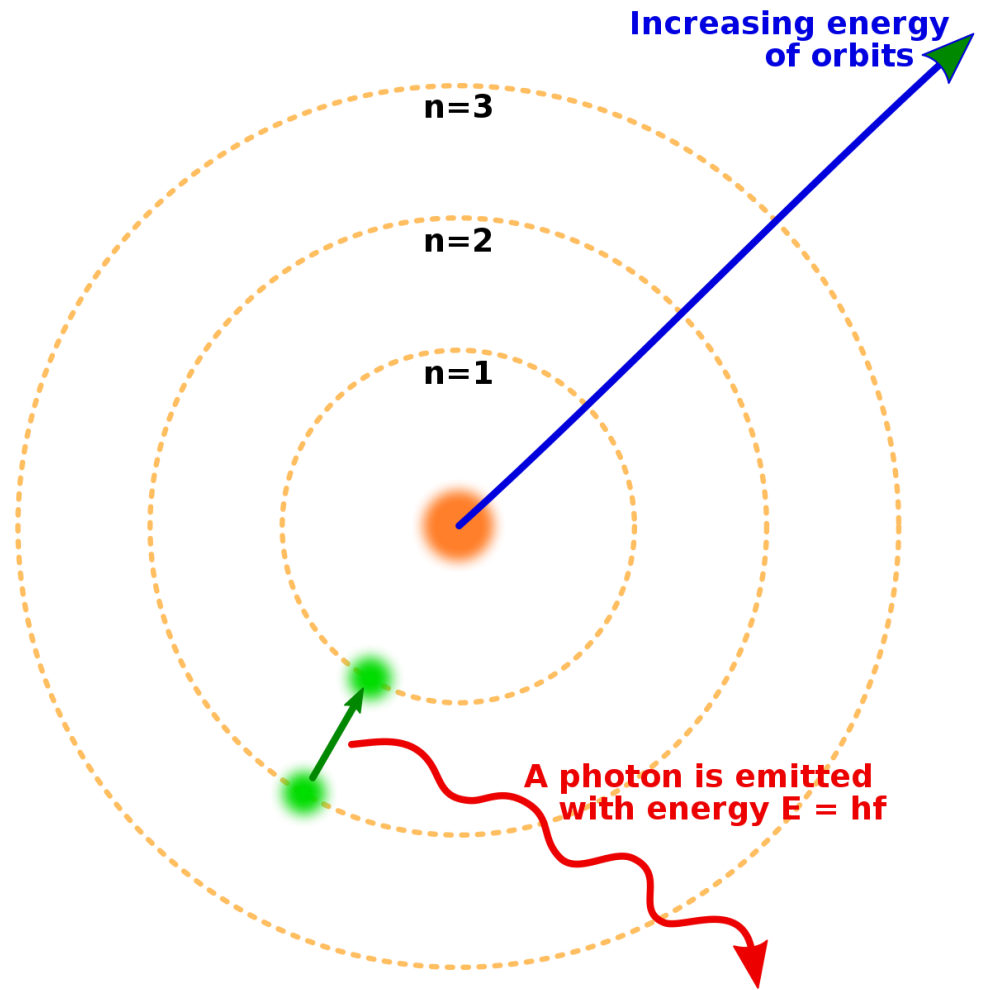
0
 $\frac{1}{2}$



**tau
neutrino**

(and their anti-particles!)

And their neutrinos, neutrinos!



e^{-}

An electron, already you will know

ELECTRON MASS

$$m_e = 9.109 \times 10^{-31} \text{ kg}$$

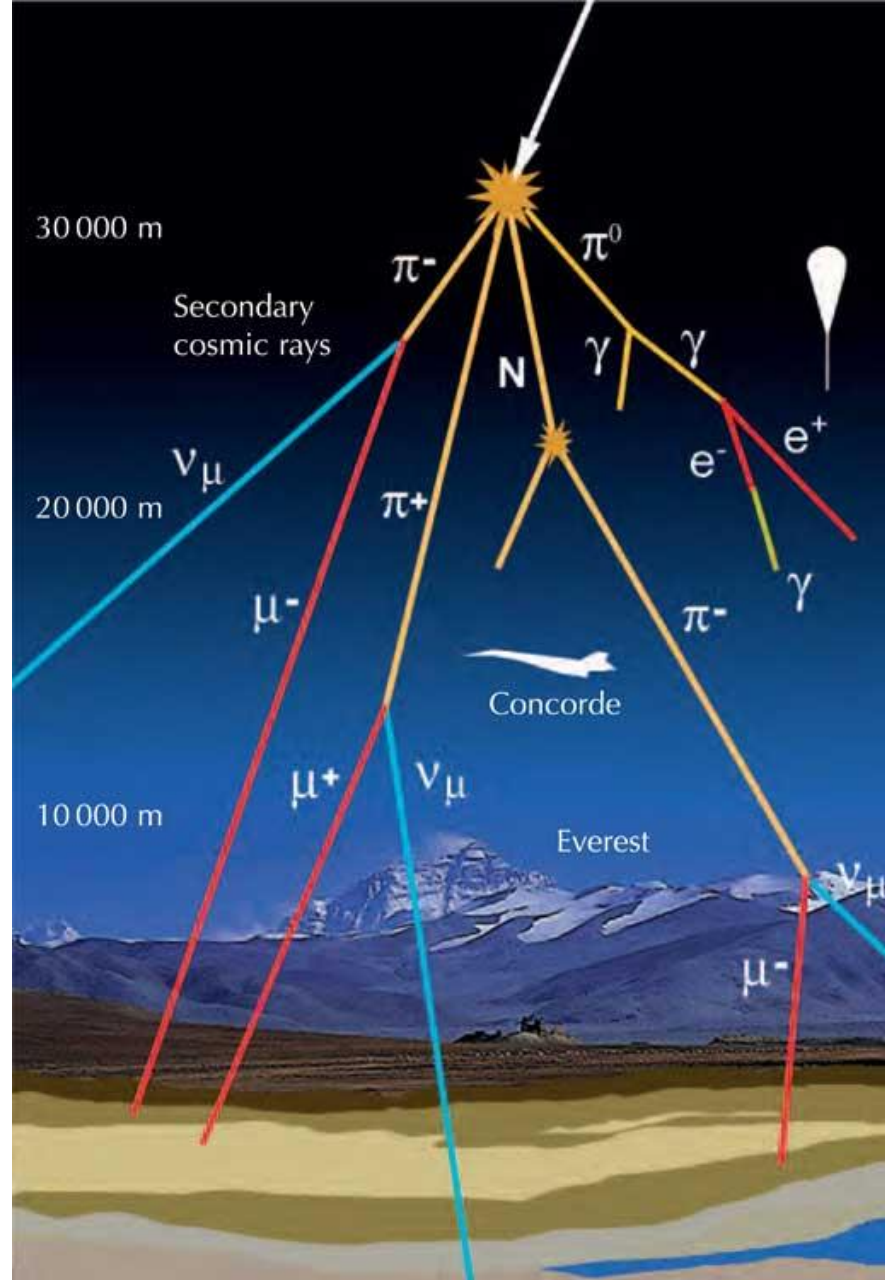
$$m_e = 0.511 \text{ MeV}/c^2$$

Is pretty small

ELECTRON CHARGE

$$e = 1.602 \times 10^{-19} \text{ C}$$

It's negatively charged



Muons made, from cosmic rays

$$m_e = 9.109 \times 10^{-31} \text{ kg}$$

$$m_\mu \approx 206.77 m_e$$

Two hundred times heavier

$$m_{\mu} \approx 206.77 m_e$$

$$m_{\tau} \approx 17 m_{\mu}$$

**And tau, tau, tau,
much more massive still**

$<1.0 \text{ eV}/c^2$

0

$\frac{1}{2}$



**electron
neutrino**

$<0.17 \text{ MeV}/c^2$

0

$\frac{1}{2}$



**muon
neutrino**

$<18.2 \text{ MeV}/c^2$

0

$\frac{1}{2}$



**tau
neutrino**

**But what about
neutrinos?**



Wolfgang Pauli
(1900-1958)

$<1.0 \text{ eV}/c^2$

0

$\frac{1}{2}$

ν_e

**electron
neutrino**

$<0.17 \text{ MeV}/c^2$

0

$\frac{1}{2}$

ν_μ

**muon
neutrino**

$<18.2 \text{ MeV}/c^2$

0

$\frac{1}{2}$

ν_τ

**tau
neutrino**

They don't have a charge

$$m_\nu < 2.14 \times 10^{-37} \text{ kg}$$

But might have a bit of mass

To detect them is a pain in the ass!

Neutrino transformed
into μ -meson

Proton path

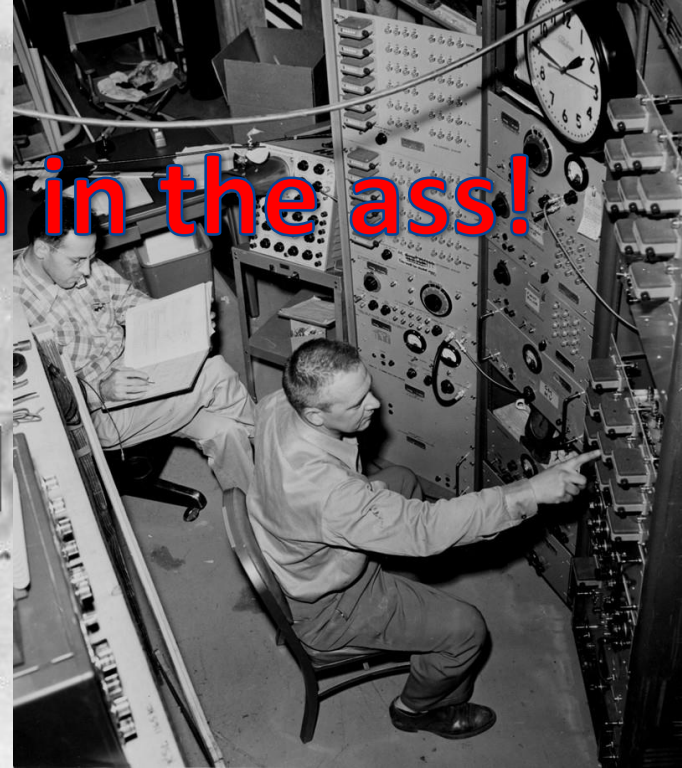
Invisible neutrino
collides with proton

Collision creates
 π -meson

The 'Neutrino Event'

Nov. 13, 1970 — World's first
observation of a neutrino in a
hydrogen bubble chamber

29

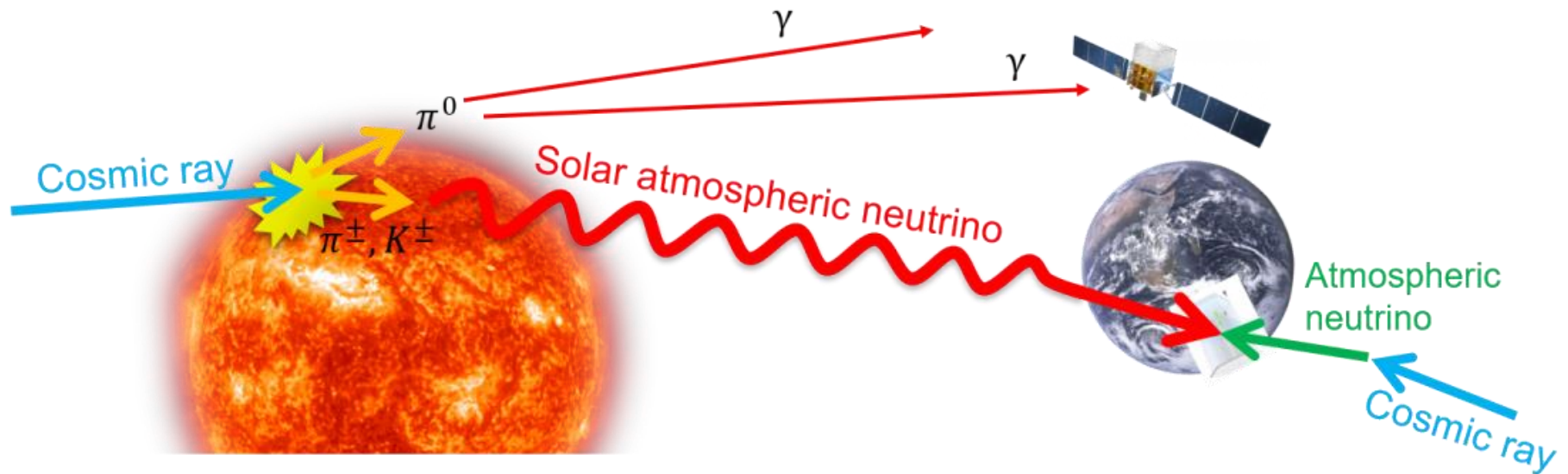


スーパーカミオカンデ

Super-Kamiokande



Reaction	Label	Flux $cm^{-1}s^{-1}$
$p + p \rightarrow {}^2H + e^+ + \nu_e$	pp	$5.95 \cdot 10^{10}$
$p + e^- + p \rightarrow {}^2H + \nu_e$	pep	$1.40 \cdot 10^8$
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	hep	$9.3 \cdot 10^3$
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	7Be	$4.77 \cdot 10^9$
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	8B	$5.05 \cdot 10^6$
${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$	${}^{13}N$	$5.48 \cdot 10^8$
${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$	${}^{15}O$	$4.80 \cdot 10^8$
${}^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$	${}^{17}F$	$5.63 \cdot 10^6$



**Trillions of them
are now passing through you**

$\approx 0.511 \text{ MeV}/c^2$

-1

$\frac{1}{2}$



electron

$\approx 105.66 \text{ MeV}/c^2$

-1

$\frac{1}{2}$



muon

$\approx 1.7768 \text{ GeV}/c^2$

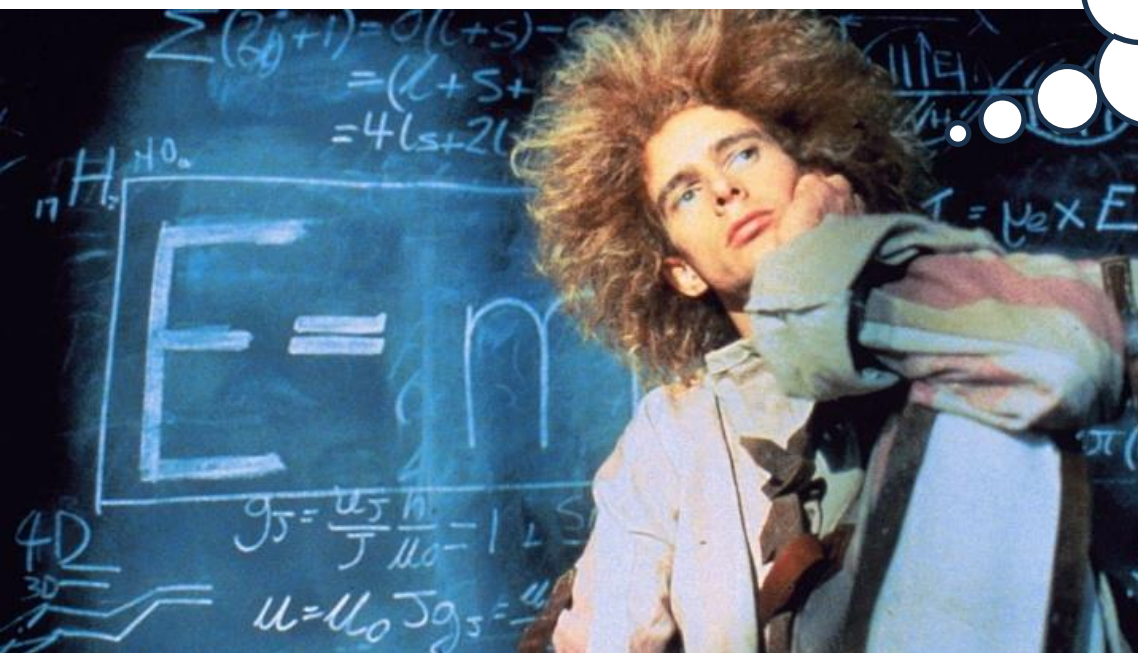
-1

$\frac{1}{2}$



tau

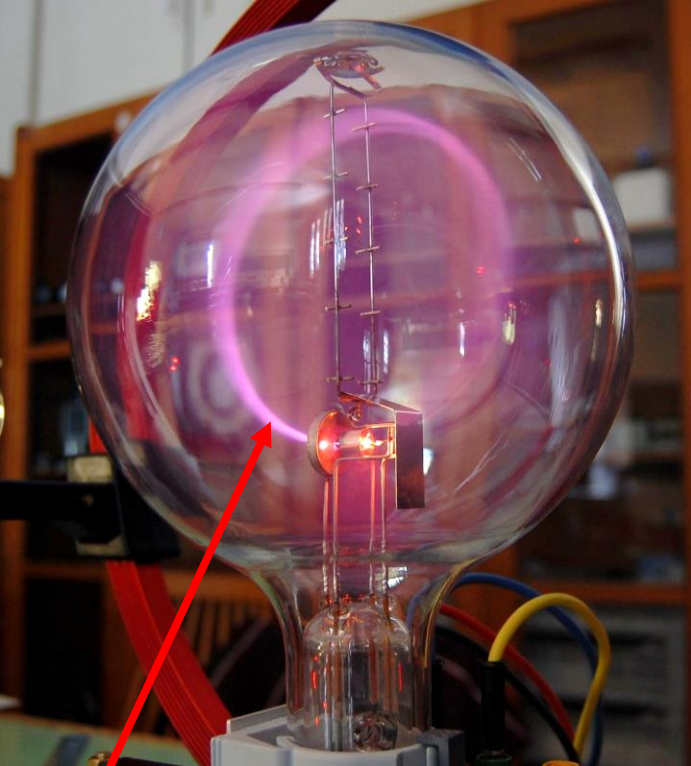
e, mu and tau



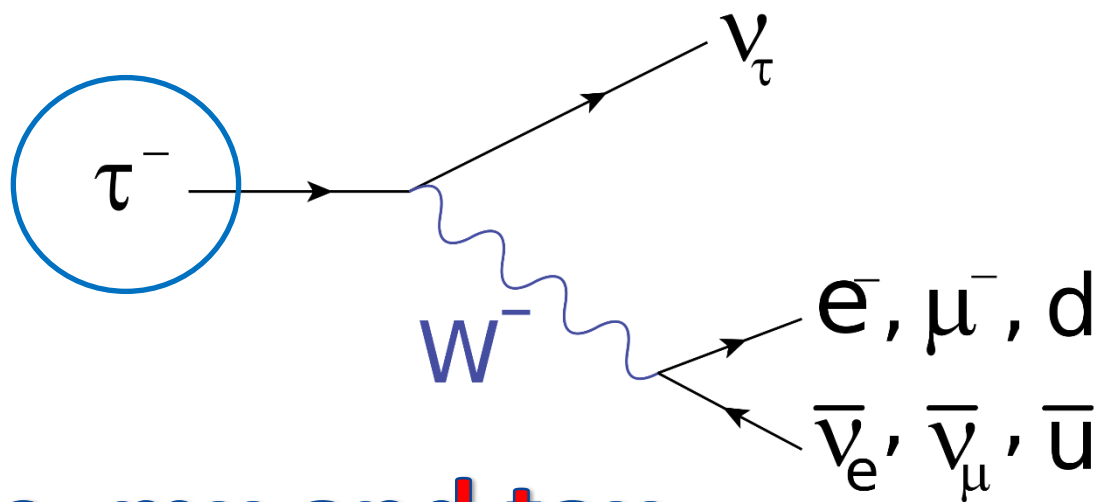
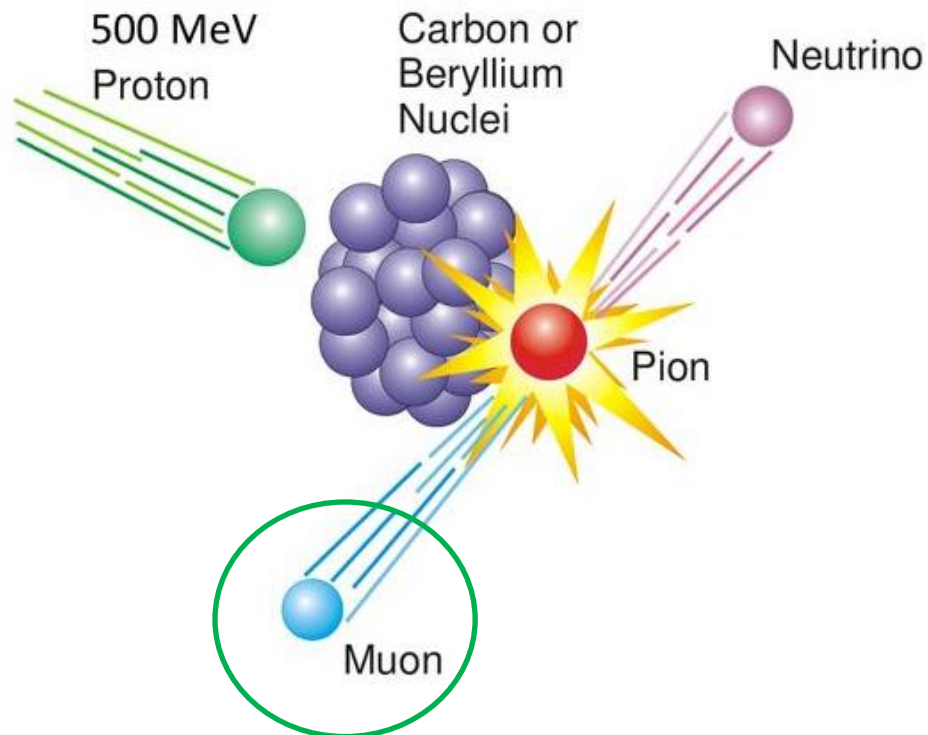
You can try,
but it won't
work!



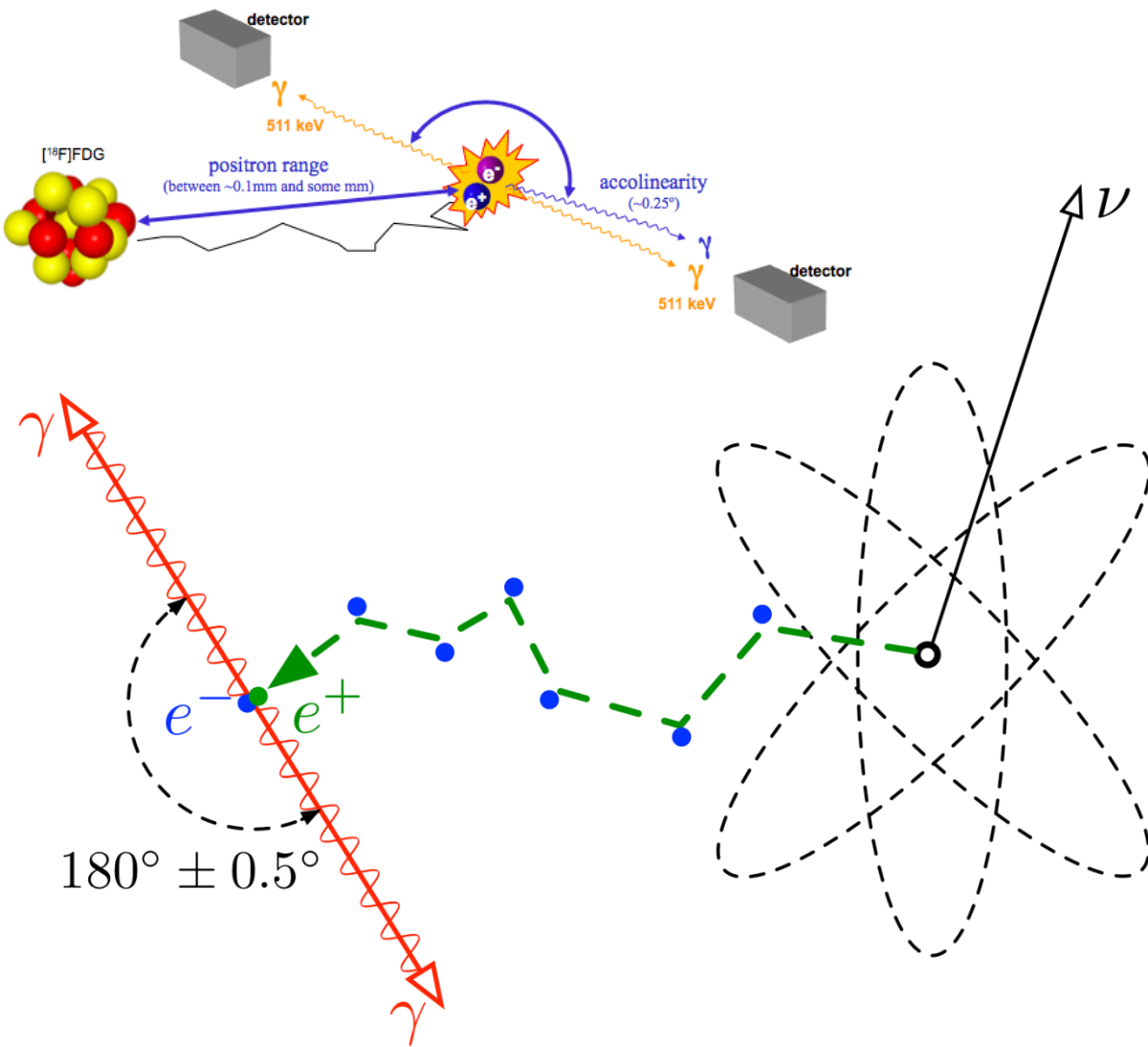
**They're fundamental
can't split an electron**



e^-



e, mu and tau



e^+ positron

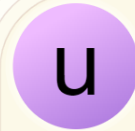





e^- electron

ν neutrino

γ quantum/photon
(511 keV)

**Add a positron
and make two photons!**

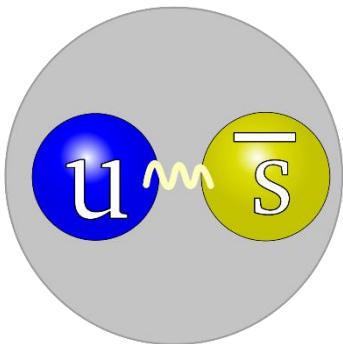
three generations of matter (fermions)

	I	II	III
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
QUARKS	 u up	 c charm	 t top
	 d down	 s strange	 b bottom

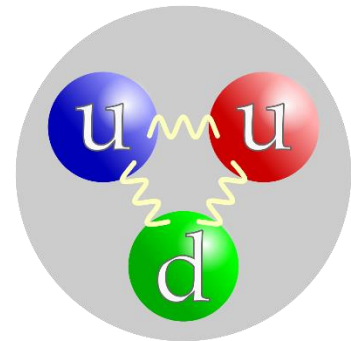


Murray Gell-Mann
(1929-2019)

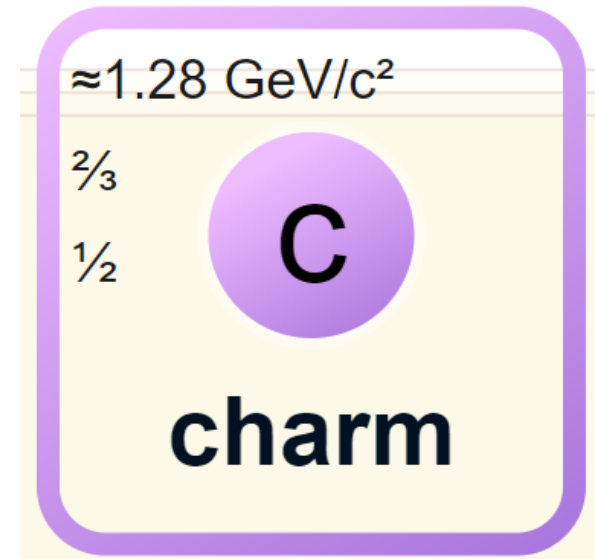
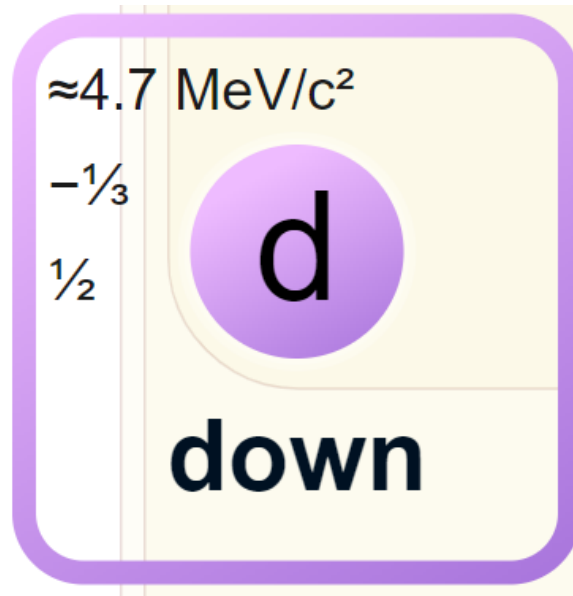
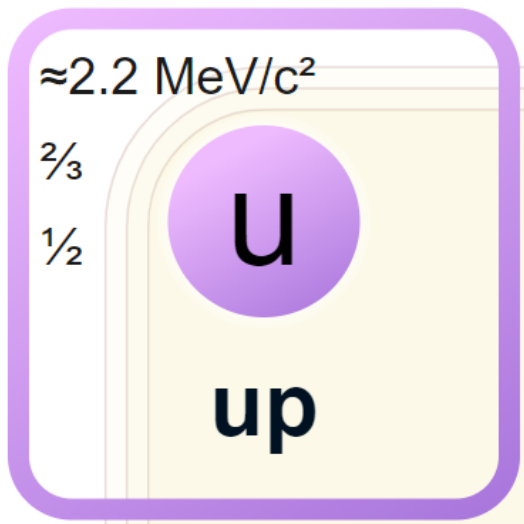
**But what about the
quarks?
(In pairs or triplets)**



kaon (+)



proton



There's up, down and charm



$\approx 96 \text{ MeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$

S

strange

$\approx 4.18 \text{ GeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$

b

bottom

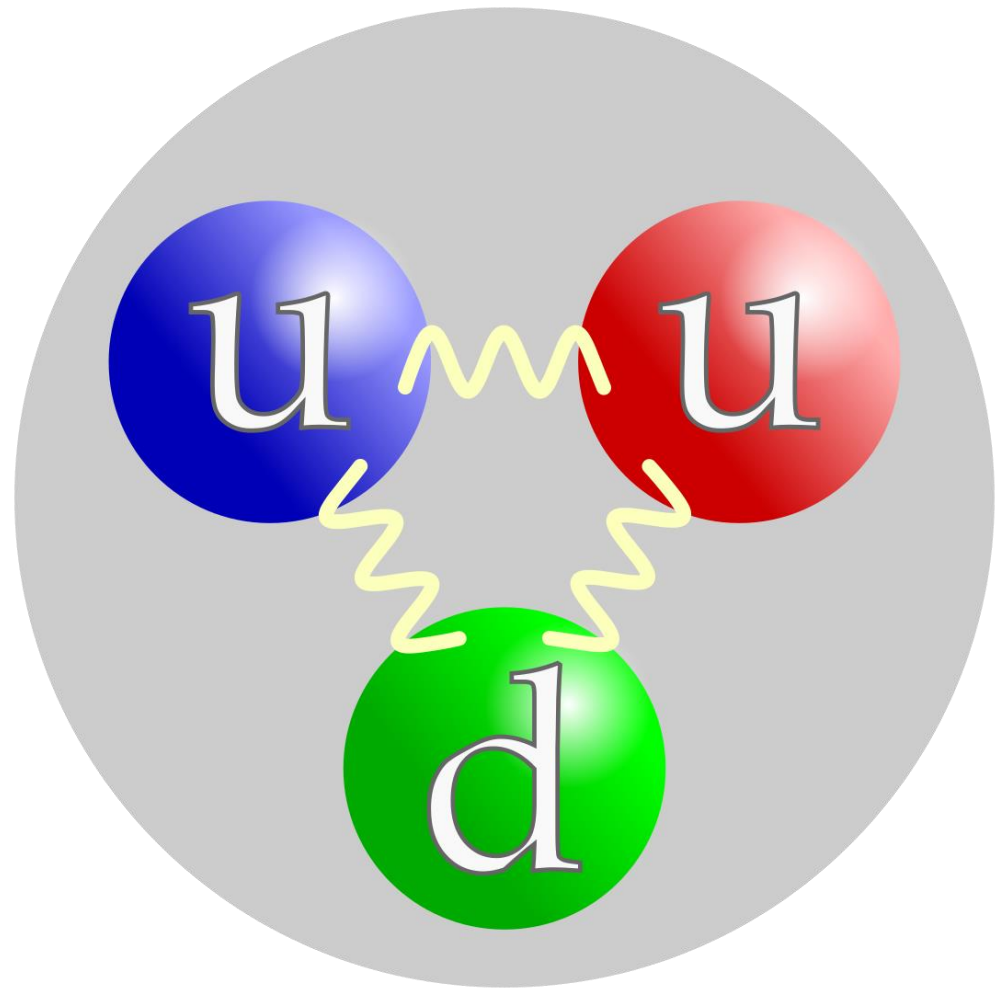


$\approx 173.1 \text{ GeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$

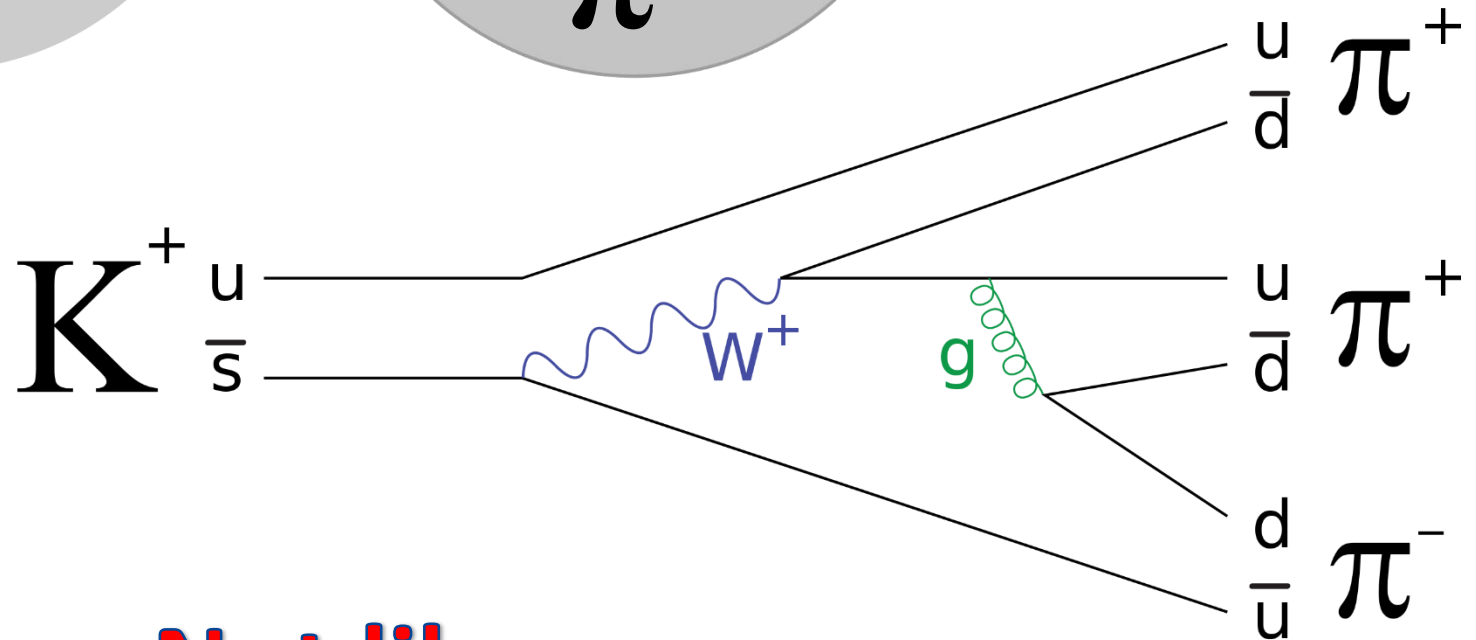
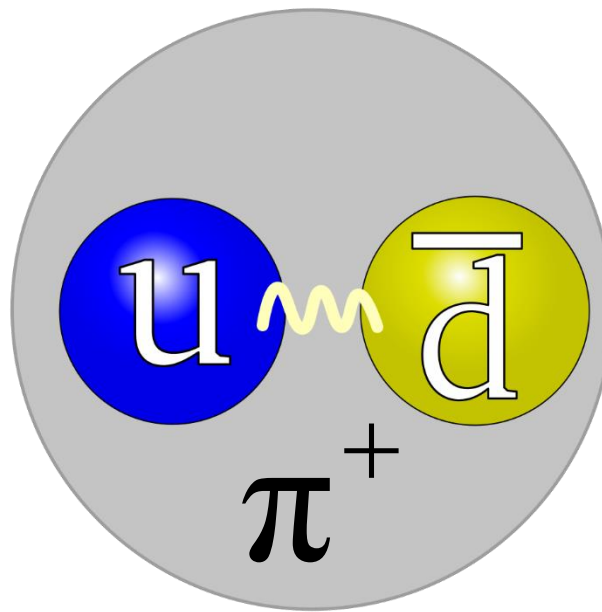
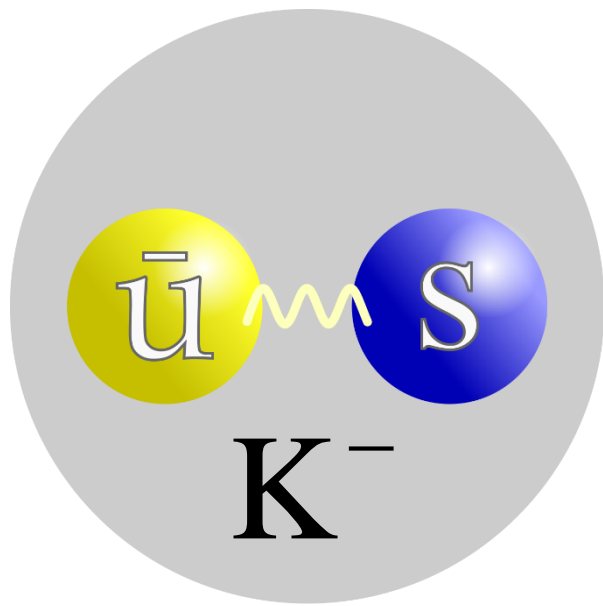
t

top

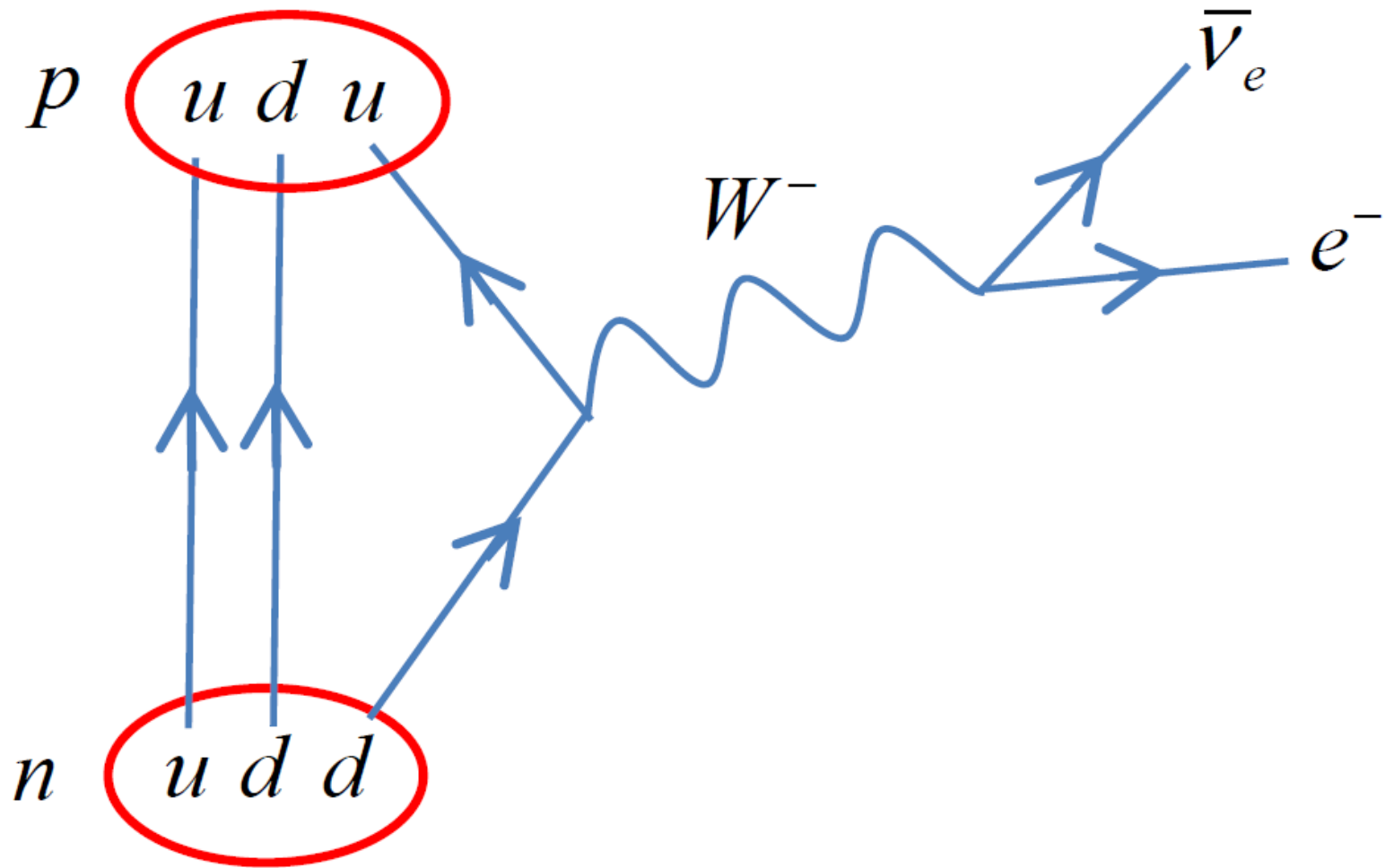
And strange, bottom and top...



**A proton is: up, up and down
in a baryon**



**Not like a meson
(a quark and anti-quark pair)**



**In a nucleus, neutrons might decay
to protons, leptons too**

$$\Delta E \Delta t \geq \hbar$$

$$\Delta p \Delta x \geq \hbar$$

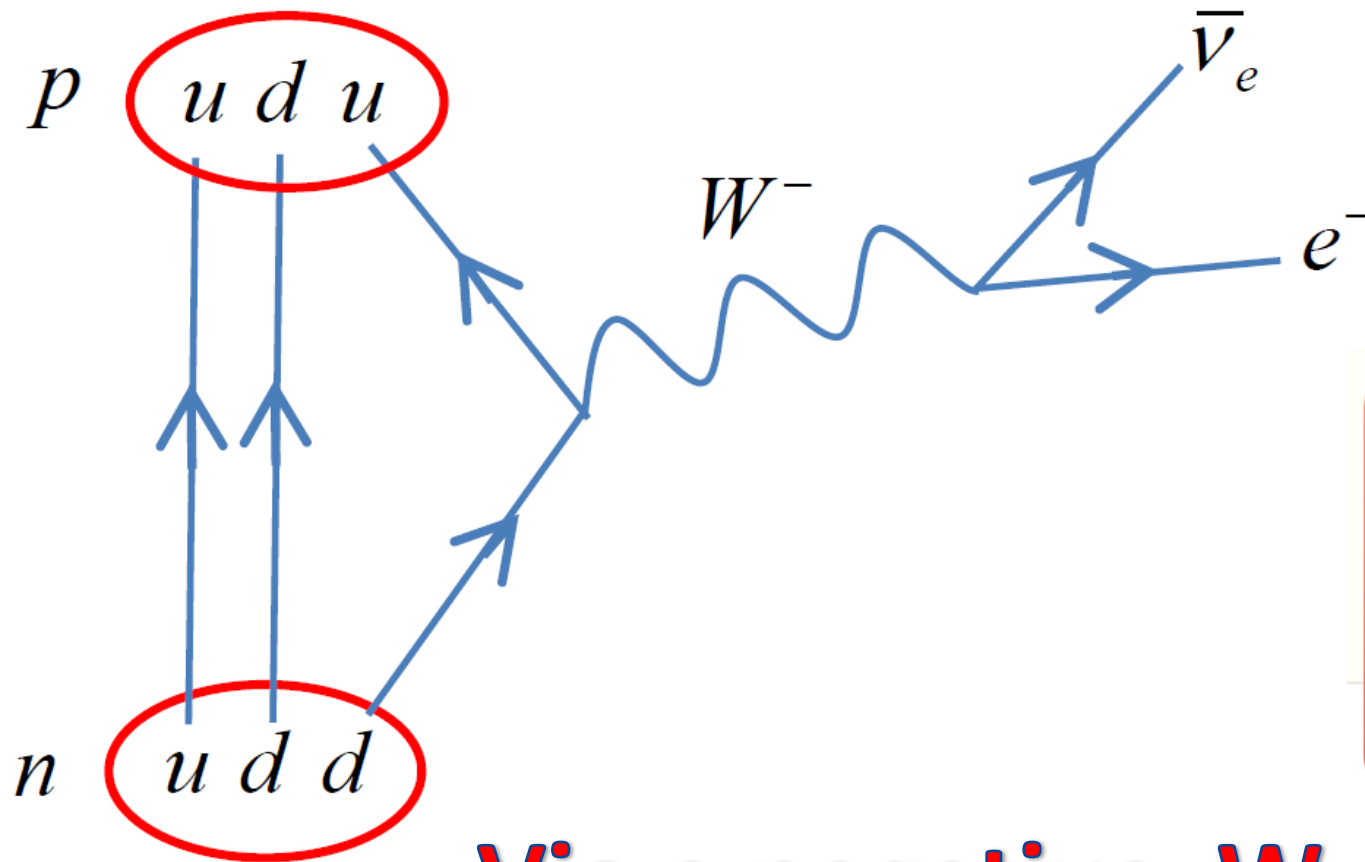
$$\Delta E \approx m_X c^2 \quad \therefore \Delta t \approx \frac{\hbar}{m_X c^2}$$

$$\Delta p \approx m_X c \quad \therefore \Delta x \approx \frac{\hbar}{m_X c}$$

$$m_{W^\pm} = \frac{80.39 \times 10^9 \times 1.602 \times 10^{-19}}{(2.998 \times 10^8)^2} = 1.433 \times 10^{-25} \text{ kg}$$

$$\therefore \Delta t \approx \frac{\hbar}{m_X c^2} = 8.19 \times 10^{-27} \text{ s} \quad \text{i.e. a very small time!}$$

$$\therefore \Delta x \approx \frac{\hbar}{m_X c} = 2.45 \times 10^{-18} \text{ m} \quad \text{i.e. sub-atomic distances}$$



$$\approx 80.360 \text{ GeV}/c^2$$

$$\pm 1$$

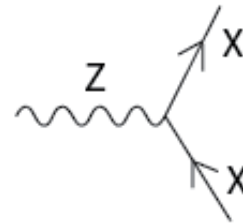
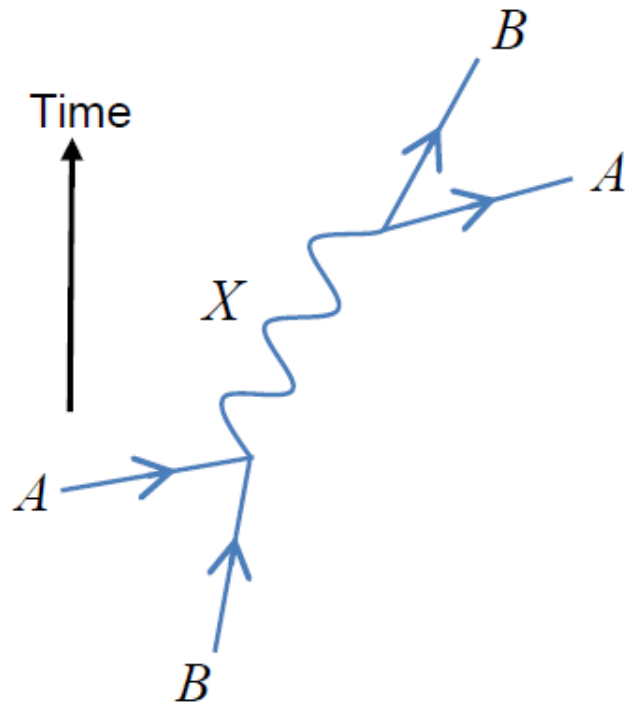
$$1$$

W

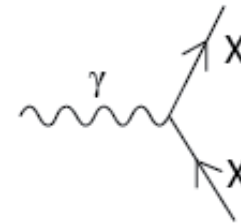
W boson

Via a negative, W

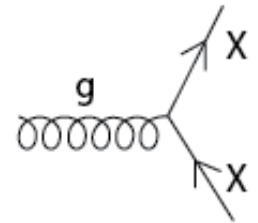
Standard Model Interactions (Forces Mediated by Gauge Bosons)



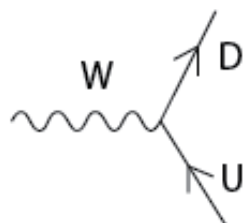
X is any fermion in the Standard Model.



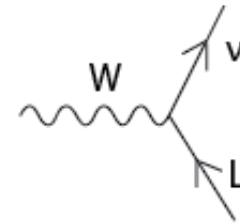
X is electrically charged.



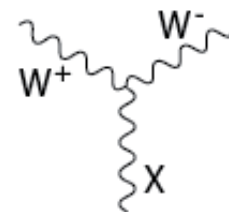
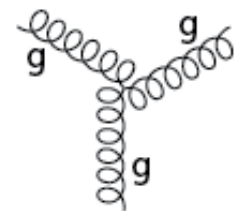
X is any quark.



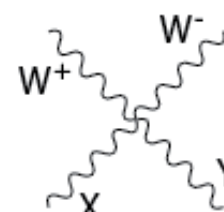
U is a up-type quark;
D is a down-type quark.



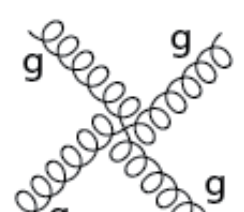
L is a lepton and ν is the corresponding neutrino.



X is a photon or Z-boson.



X and Y are any two electroweak bosons such that charge is conserved.



How do these particles interact?

0
0
1

g

gluon

$\approx 125.11 \text{ GeV}/c^2$

0
0
0

H

higgs

0
0
1

γ

photon

$\approx 91.19 \text{ GeV}/c^2$

0
1

Z

Z boson

$\approx 80.360 \text{ GeV}/c^2$

± 1
1

W

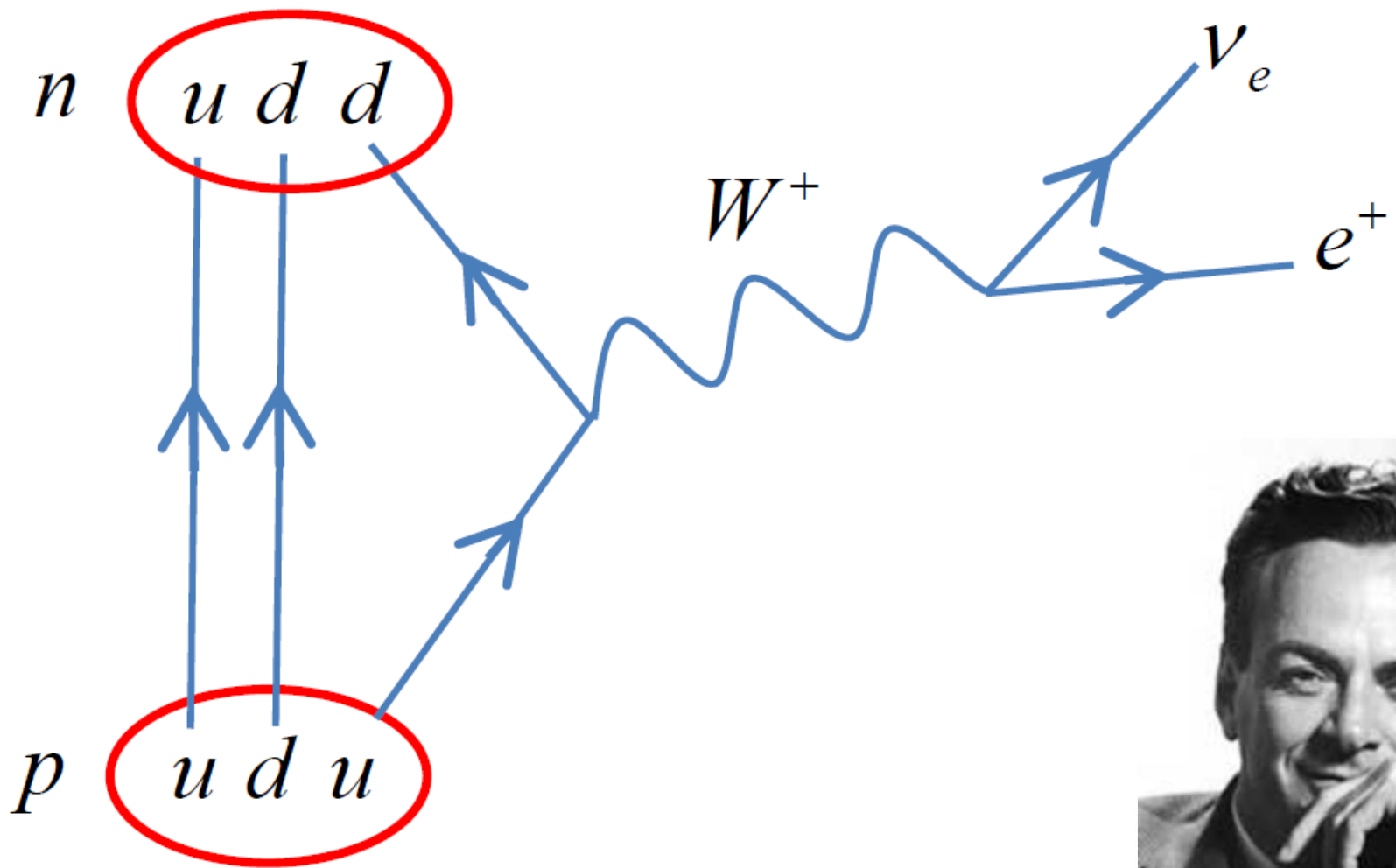
W boson

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS



(via) Bosons

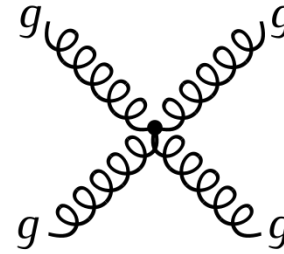
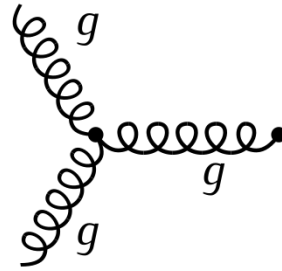
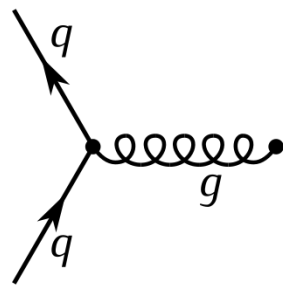


**In a Feynman
diagram**

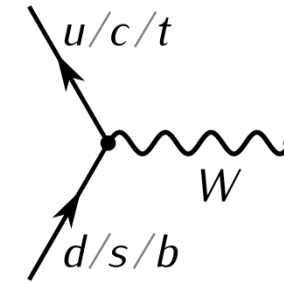
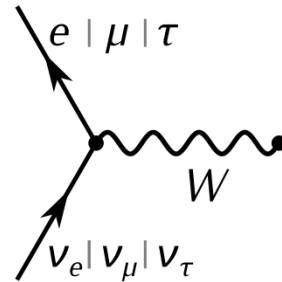
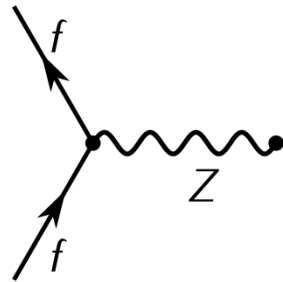


Richard Feynman
(1918-1988)

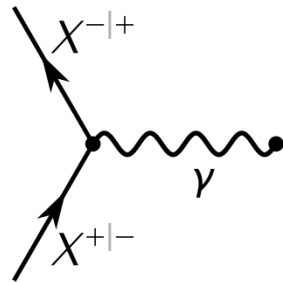
STRONG VERTICES



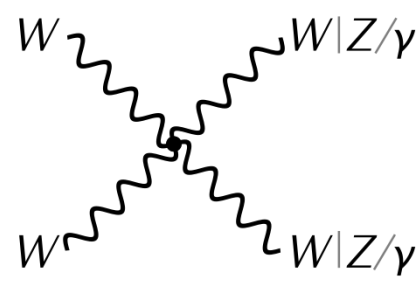
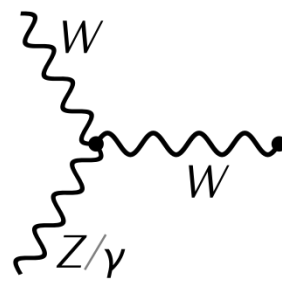
WEAK VERTICES



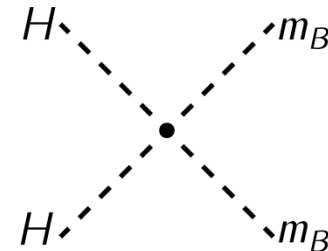
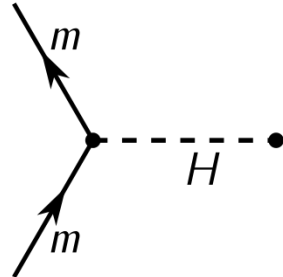
ELECTROMAGNETIC VERTEX



ELECTROWEAK VERTICES



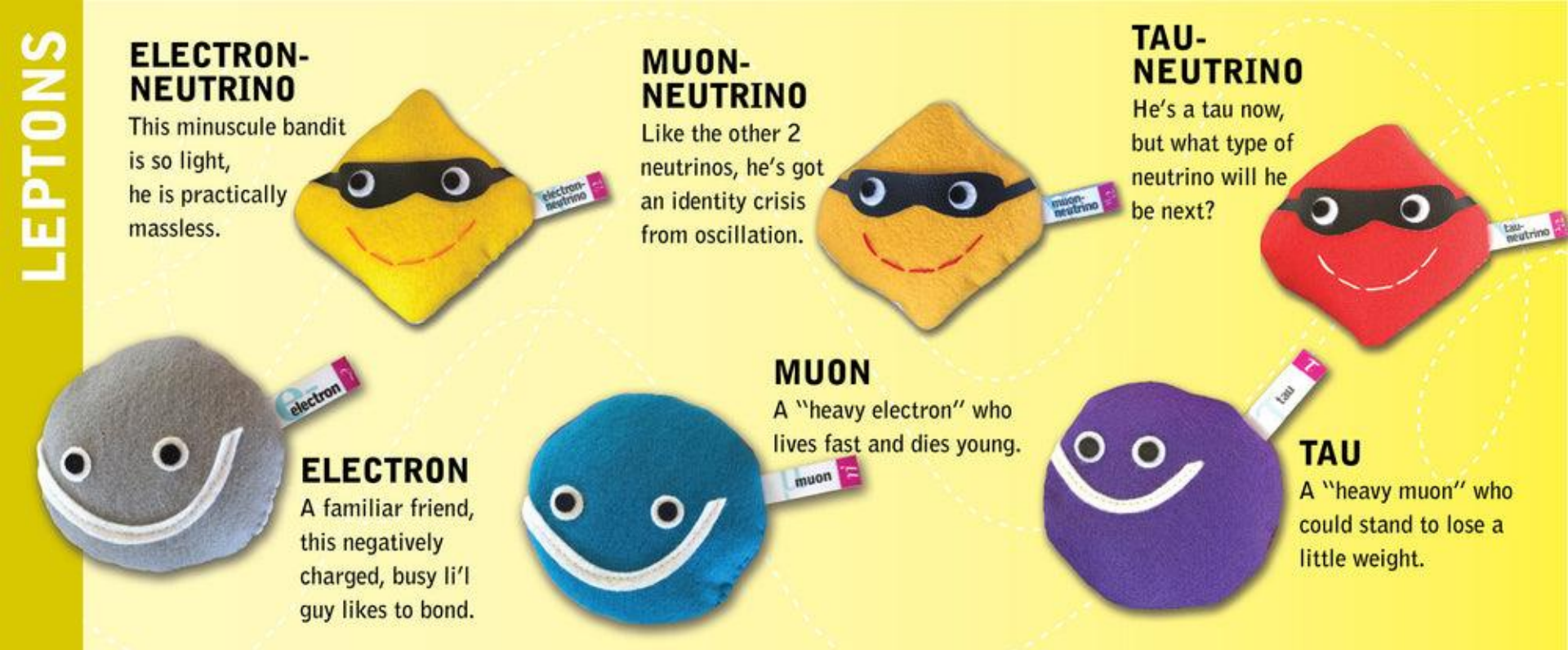
HIGGS VERTICES



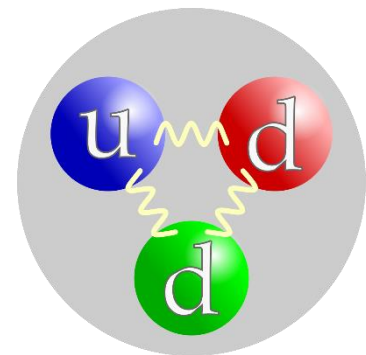
The Standard Model plan



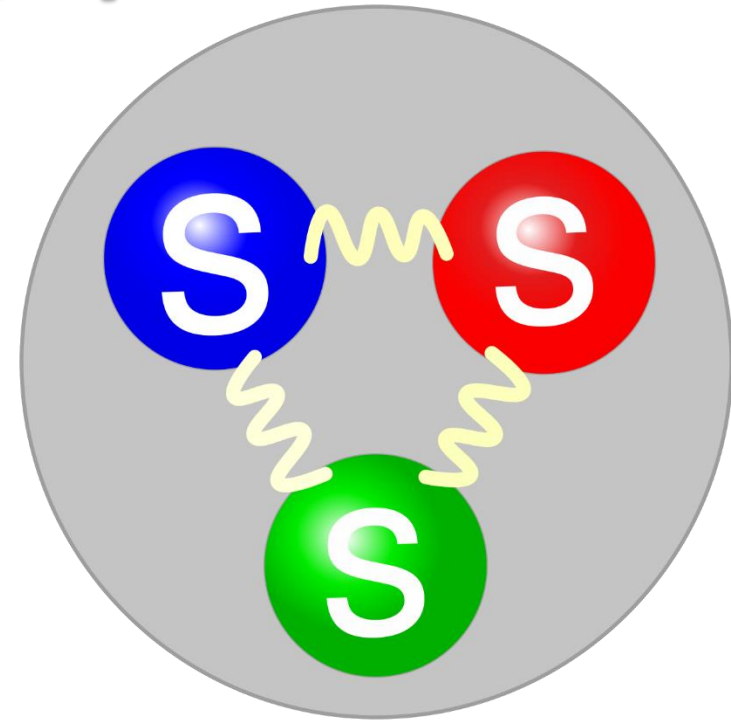
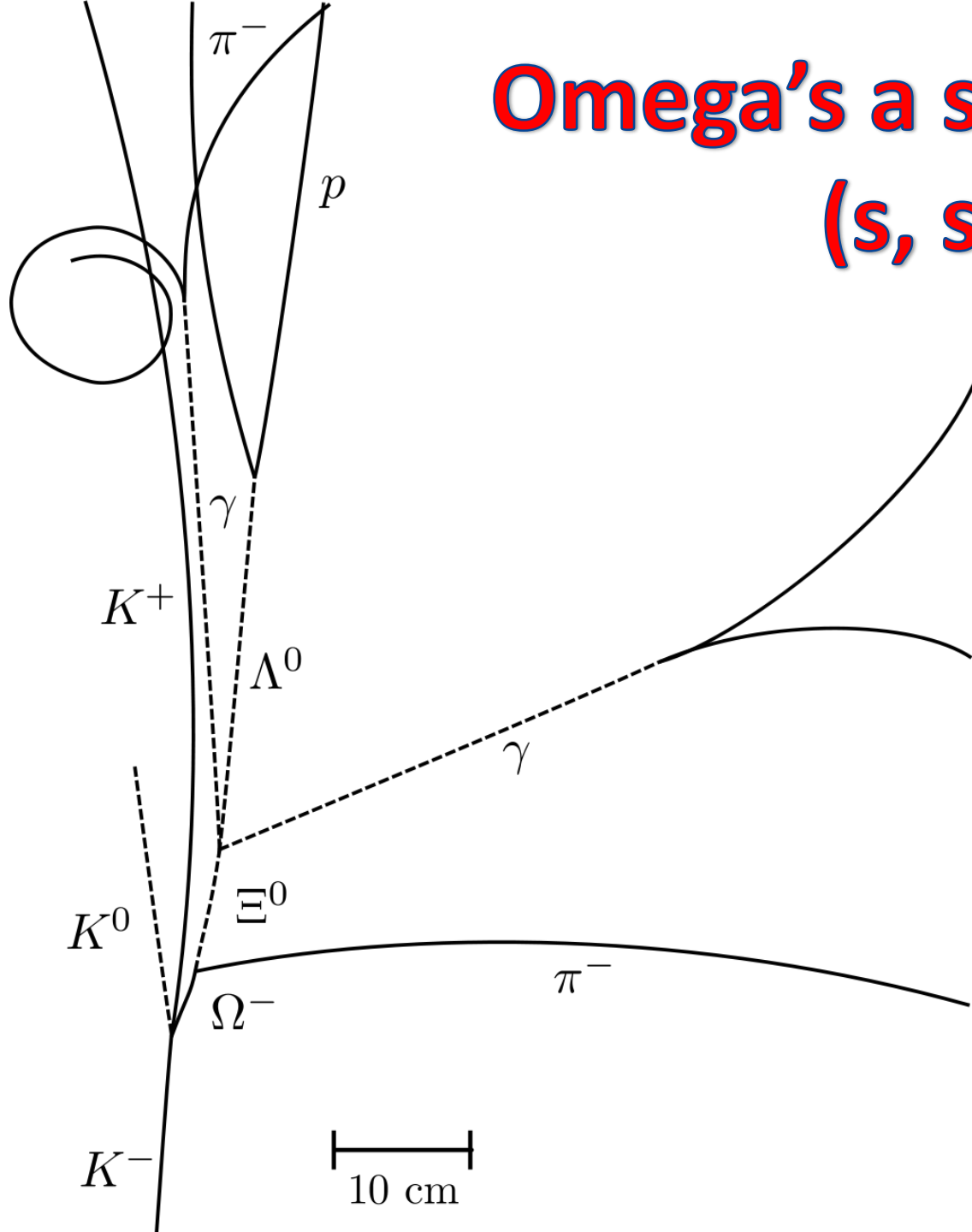
Of an accelerator near you...



**Leptons
aren't hadrons
like neutrons
(up, down, down)**

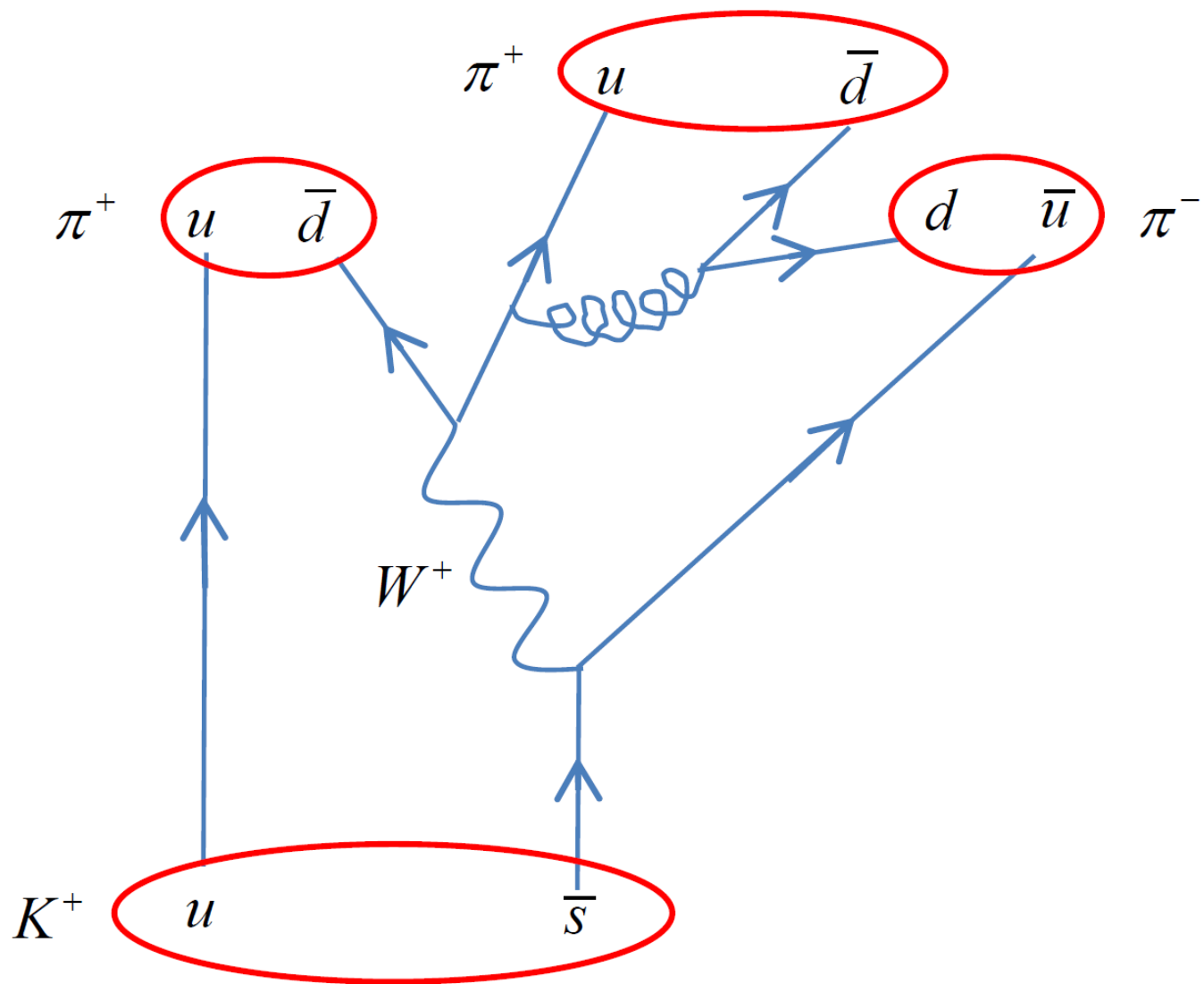


Omega's a strange one (s, s, s)



$$\Delta t \approx 8.2 \times 10^{-11} \text{ s}$$

$$m_{\Omega} \approx 1.672 \frac{\text{GeV}}{c^2}$$



**There's kaons and pions
(u s bar, u d bar)**

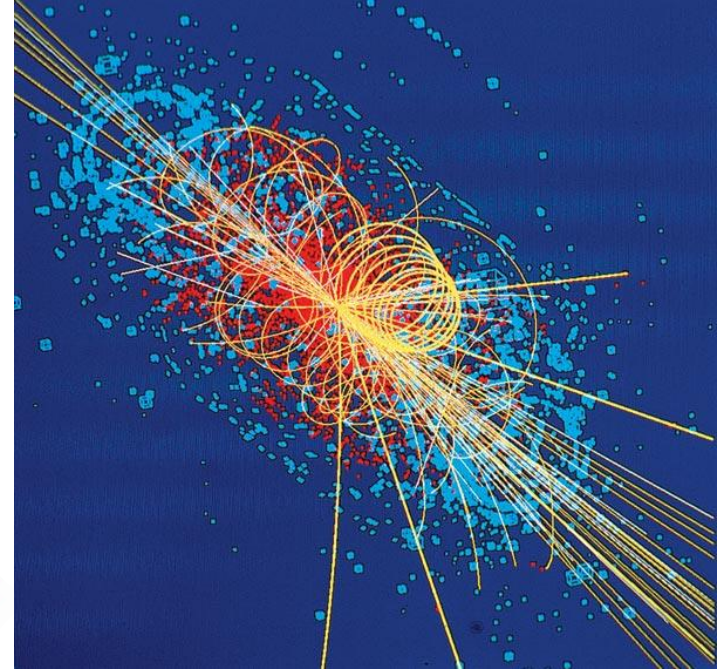
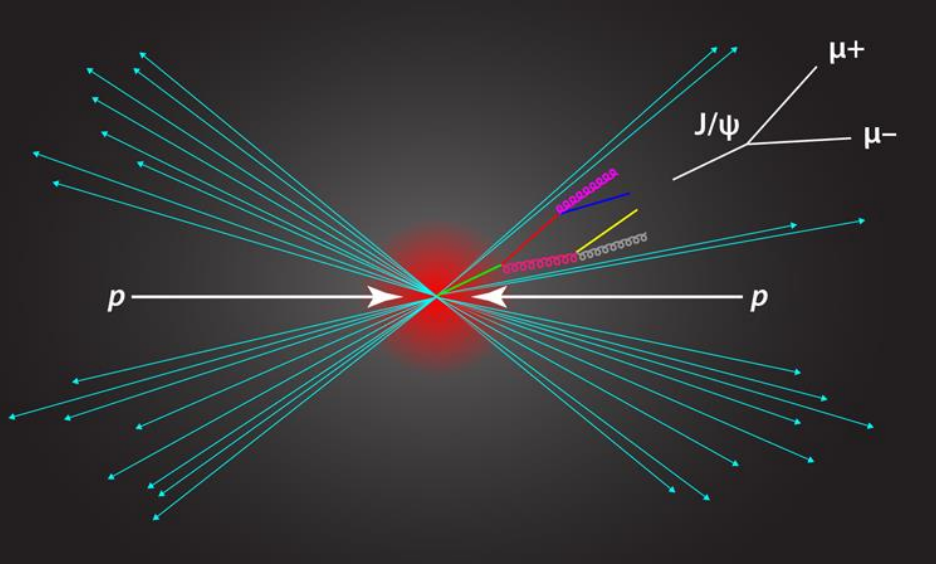
mass
charge
spin

QUARKS

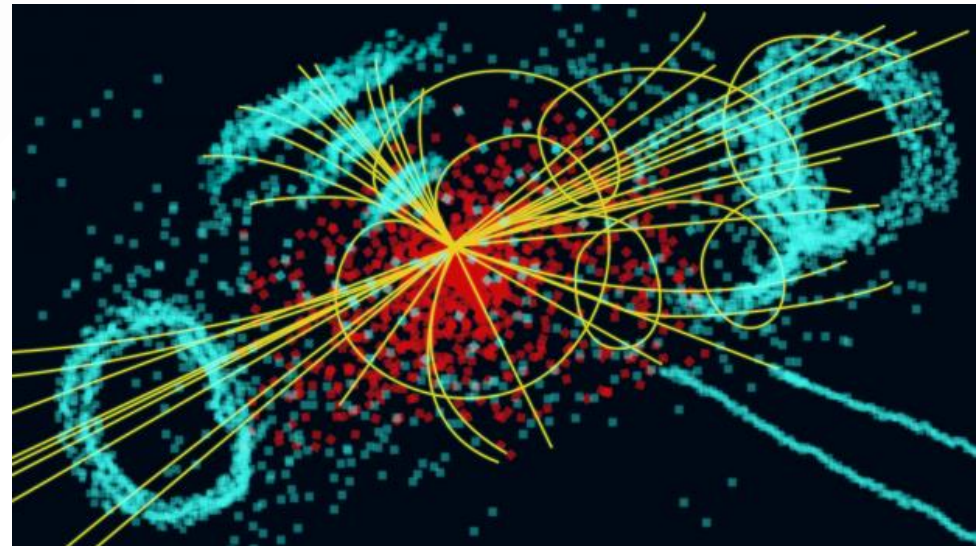
$\approx 2.2 \text{ MeV/c}^2$ $\frac{2}{3}$ $\frac{1}{2}$ u up	$\approx 1.28 \text{ GeV/c}^2$ $\frac{2}{3}$ $\frac{1}{2}$ c charm	$\approx 173.1 \text{ GeV/c}^2$ $\frac{2}{3}$ $\frac{1}{2}$ t top
$\approx 4.7 \text{ MeV/c}^2$ $-\frac{1}{3}$ $\frac{1}{2}$ d down	$\approx 96 \text{ MeV/c}^2$ $-\frac{1}{3}$ $\frac{1}{2}$ s strange	$\approx 4.18 \text{ GeV/c}^2$ $-\frac{1}{3}$ $\frac{1}{2}$ b bottom

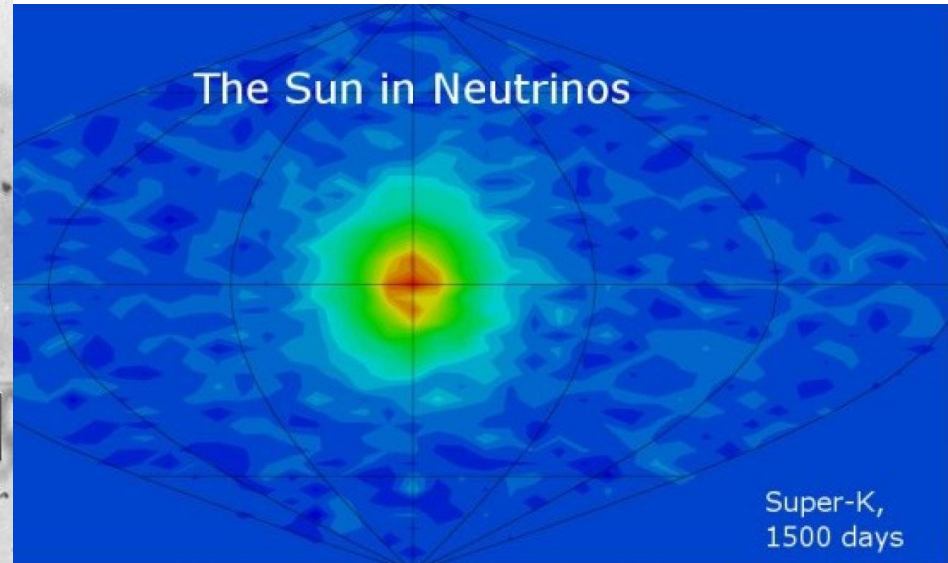
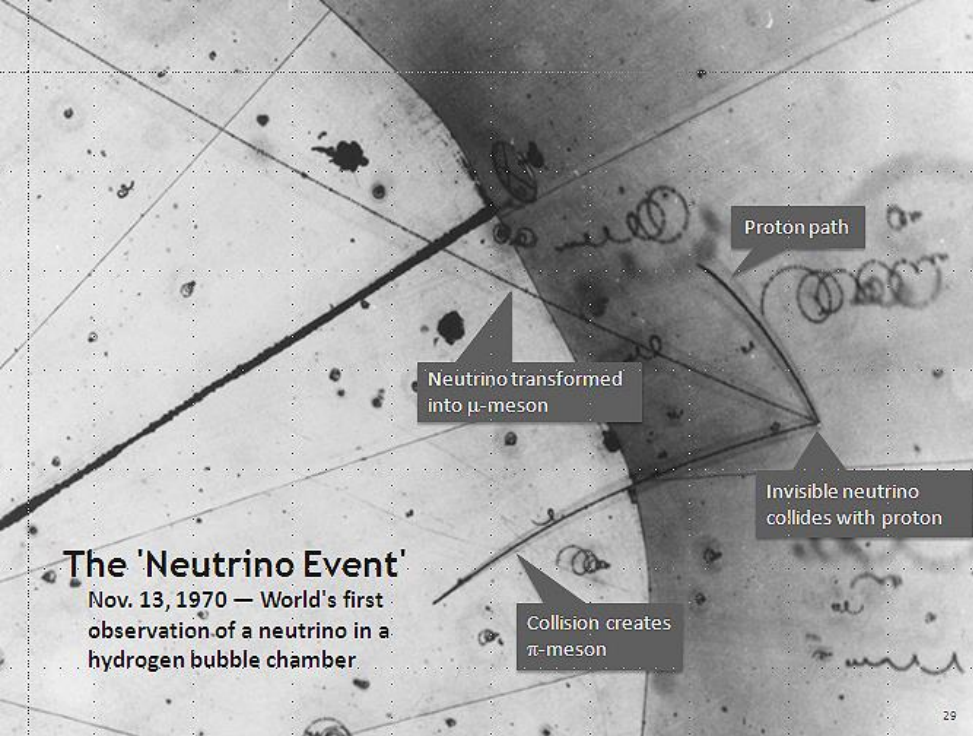


**But the quarks
with their gluons ain't free....!**



*** Amazing
guitar solo! ***





$<1.0 \text{ eV}/c^2$

0
 $\frac{1}{2}$

ν_e

**electron
neutrino**

$<0.17 \text{ MeV}/c^2$

0
 $\frac{1}{2}$

ν_μ

**muon
neutrino**




$<18.2 \text{ MeV}/c^2$

0
 $\frac{1}{2}$

ν_τ

**tau
neutrino**

I've told you about neutrinos

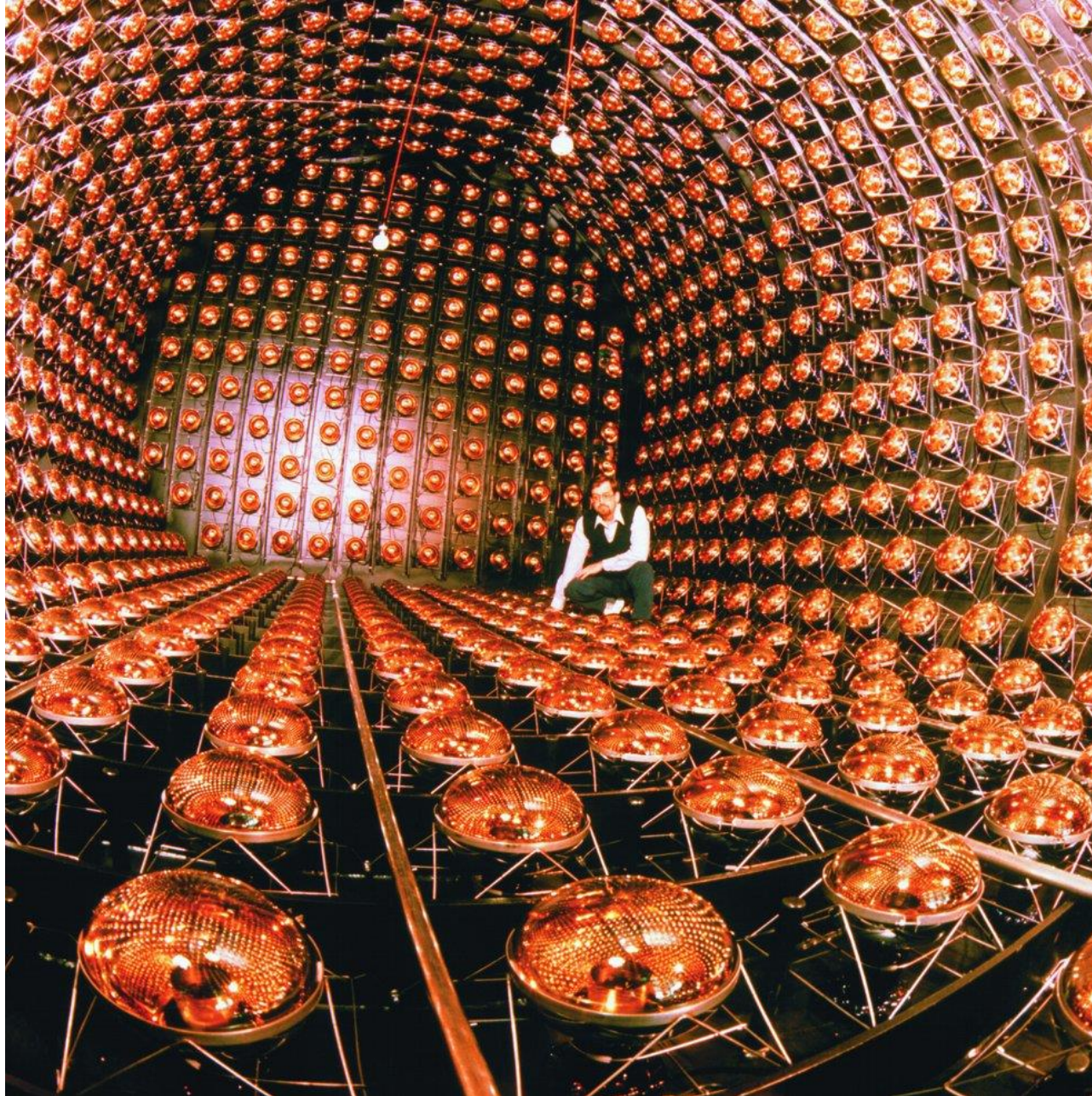
$<1.0 \text{ eV}/c^2$ 0 $\frac{1}{2}$  electron neutrino	$<0.17 \text{ MeV}/c^2$ 0 $\frac{1}{2}$  muon neutrino	$<18.2 \text{ MeV}/c^2$ 0 $\frac{1}{2}$  tau neutrino
--	---	---

They don't have a charge



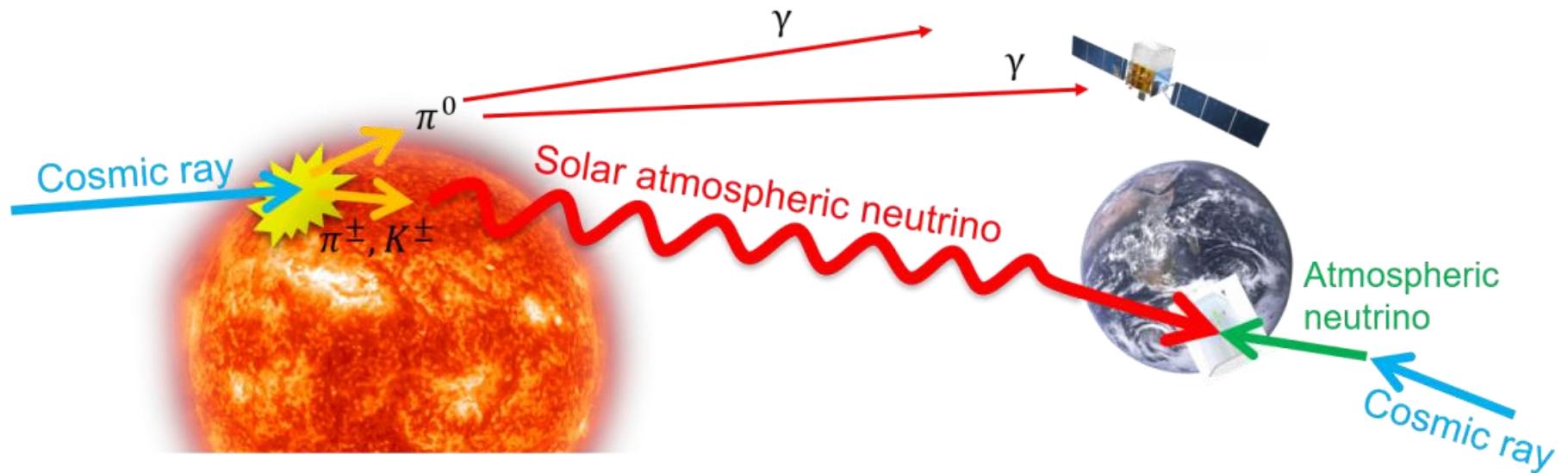
$$m_\nu < 2.14 \times 10^{-37} \text{ kg}$$

But might have a bit of mass



To detect them is a pain in the ass!

Reaction	Label	Flux $cm^{-1}s^{-1}$
$p + p \rightarrow {}^2H + e^+ + \nu_e$	pp	$5.95 \cdot 10^{10}$
$p + e^- + p \rightarrow {}^2H + \nu_e$	pep	$1.40 \cdot 10^8$
${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$	hep	$9.3 \cdot 10^3$
${}^7Be + e^- \rightarrow {}^7Li + \nu_e$	7Be	$4.77 \cdot 10^9$
${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$	8B	$5.05 \cdot 10^6$
${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$	${}^{13}N$	$5.48 \cdot 10^8$
${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$	${}^{15}O$	$4.80 \cdot 10^8$
${}^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$	${}^{17}F$	$5.63 \cdot 10^6$



**Trillions of them
are now passing through you**

$\approx 0.511 \text{ MeV}/c^2$

-1

$\frac{1}{2}$



electron

$\approx 105.66 \text{ MeV}/c^2$

-1

$\frac{1}{2}$



muon

$\approx 1.7768 \text{ GeV}/c^2$

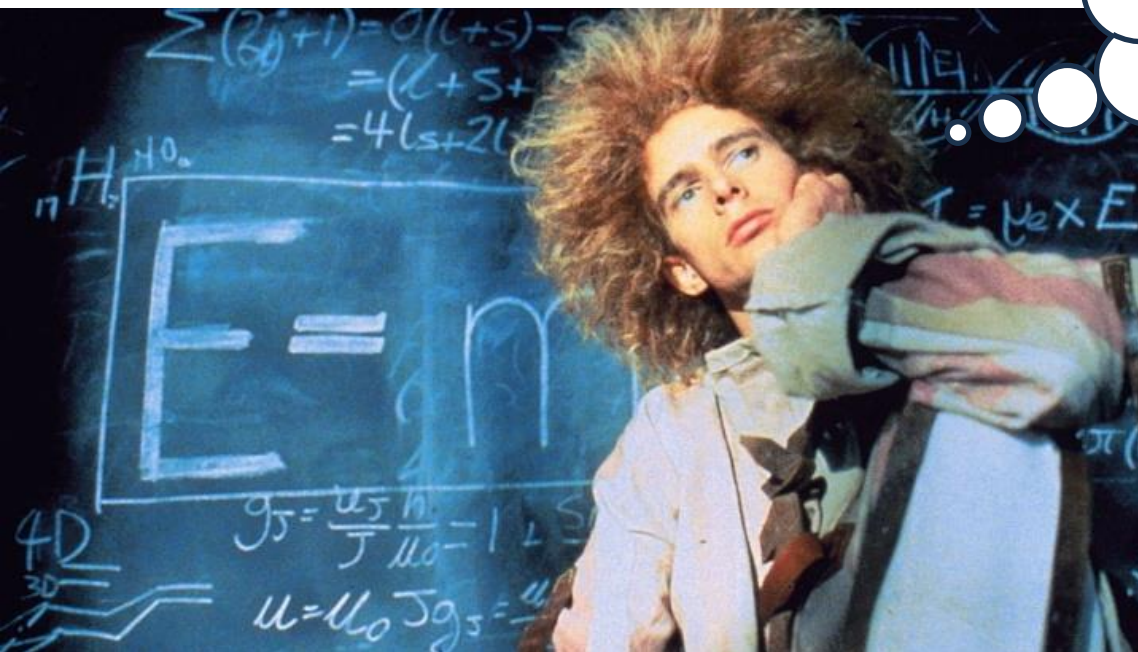
-1

$\frac{1}{2}$



tau

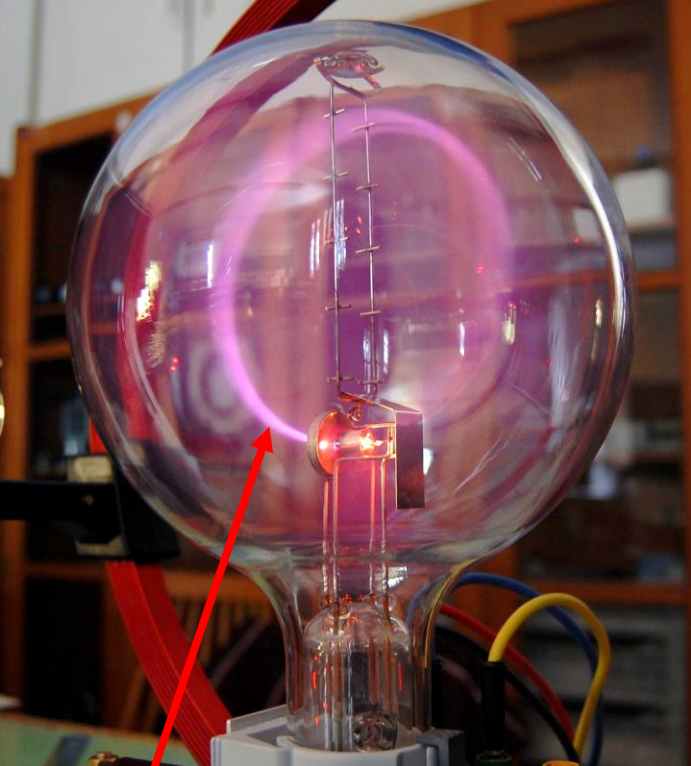
e, mu and tau



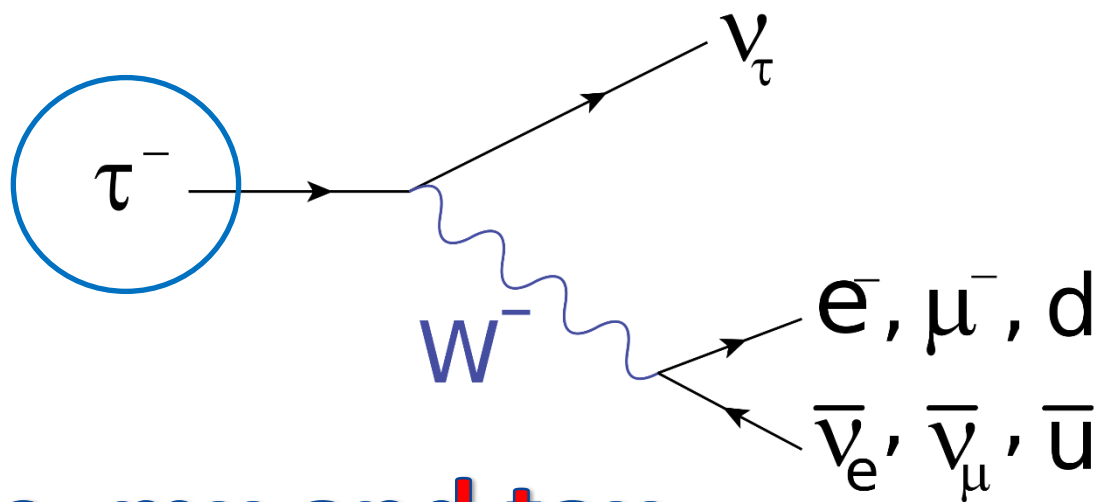
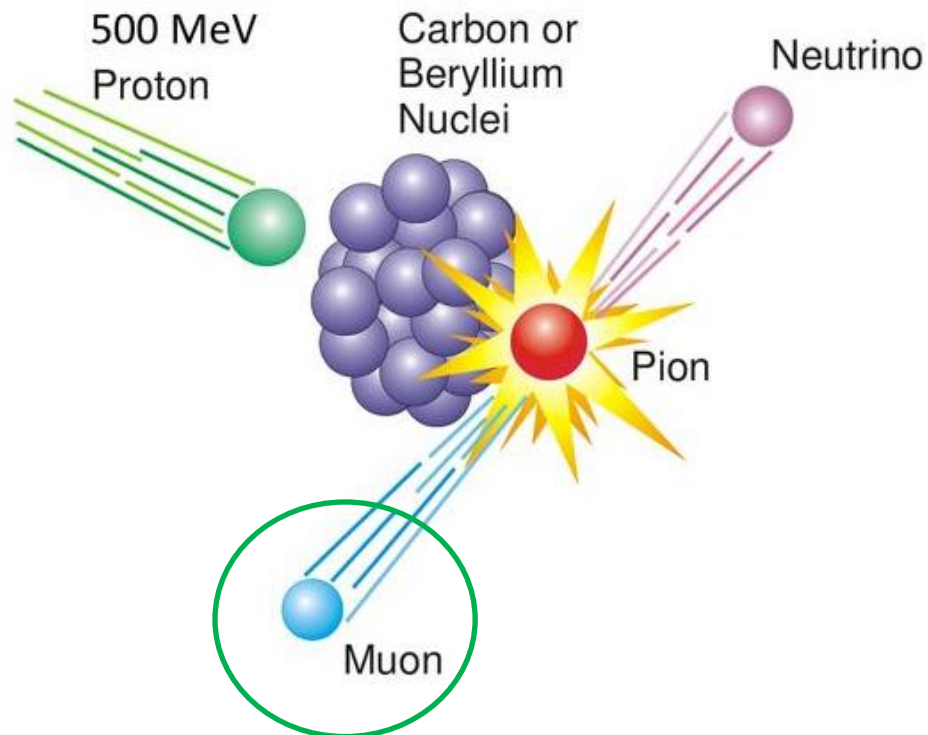
You can try,
but it won't
work!



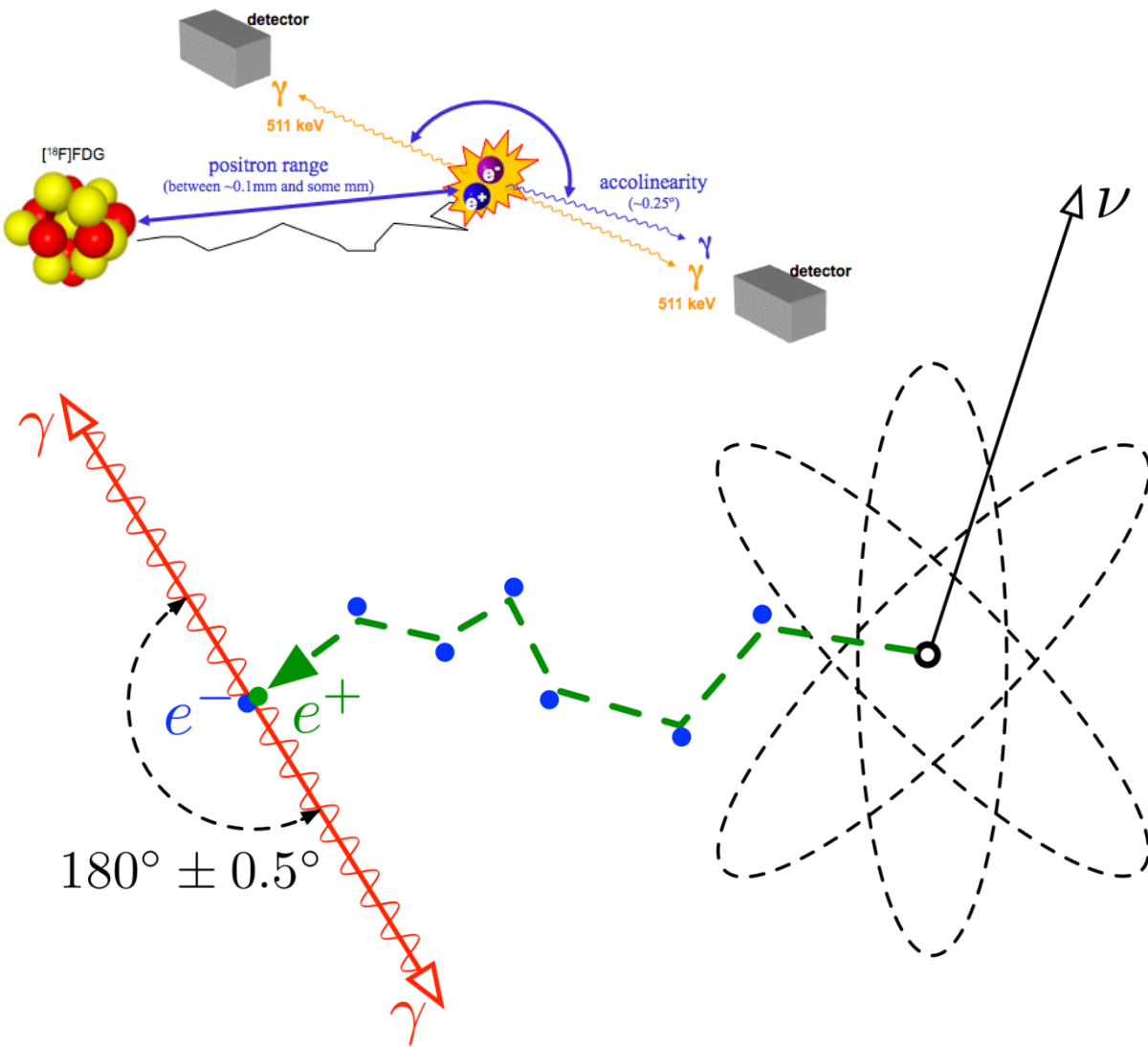
**They're fundamental
can't split an electron**



e^-



e, mu and tau



e^+ positron
 e^- electron
 ν neutrino
 γ quantum/photon
 (511 keV)

**Add a positron
and make two photons!**

QUARKS



UP QUARK

A teeny little point inside the proton and neutron, it is friends forever with the down quark.



CHARM QUARK

A charming second generation quark.



TOP QUARK

This heavyweight champion doesn't live long enough to make friends with anyone.

DOWN QUARK

A tiny little point inside the proton and neutron, it is friends forever with the up quark.



STRANGE QUARK

What's so strange about this second generation quark?

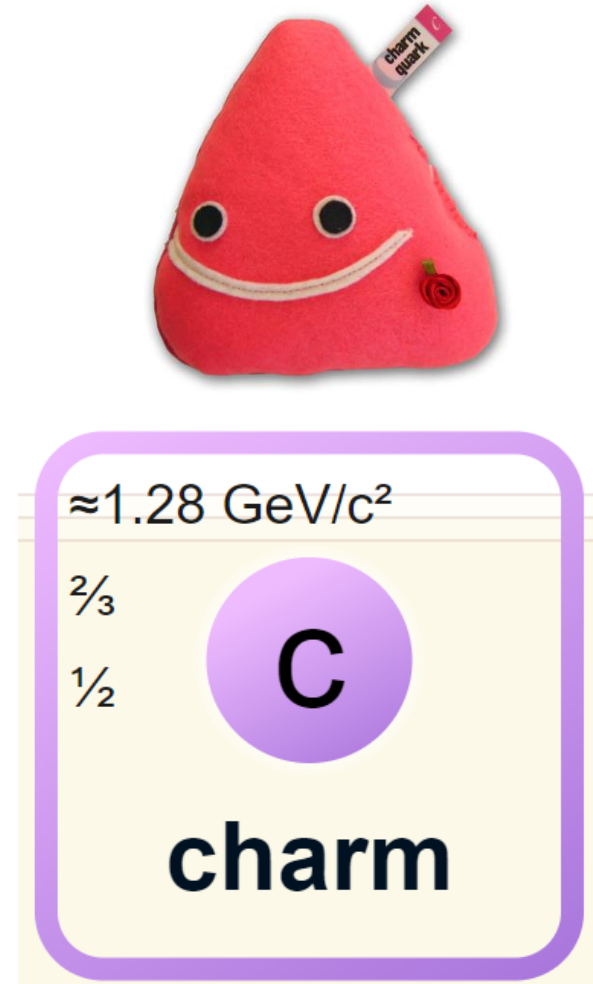
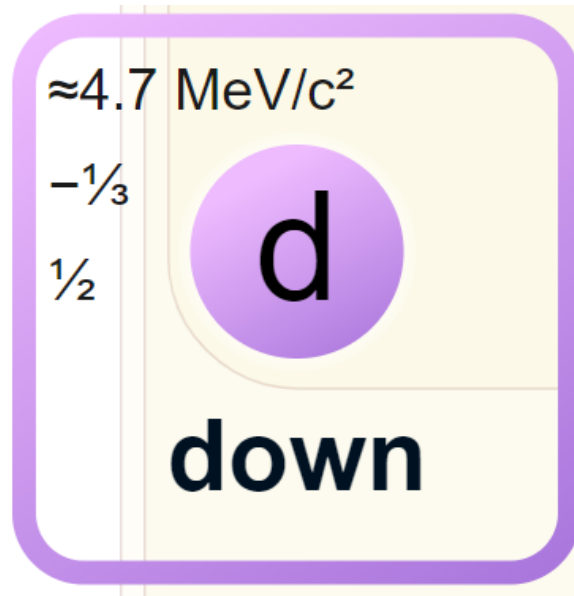
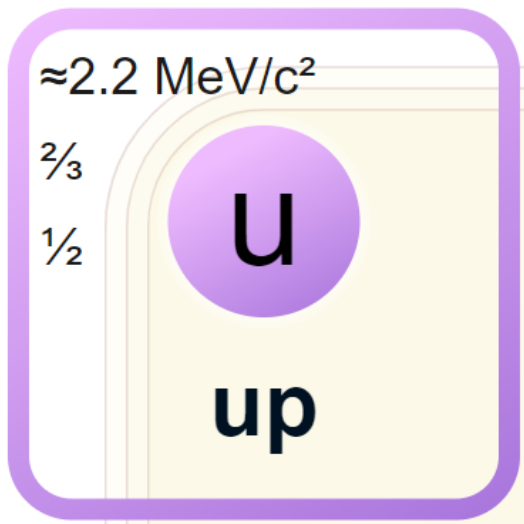


BOTTOM QUARK

This third generation quark is puttin' on the pounds.



**But what about the quarks?
(In pairs or triplets)**



There's up, down and charm



$\approx 96 \text{ MeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$

S

strange

$\approx 4.18 \text{ GeV}/c^2$
 $-\frac{1}{3}$
 $\frac{1}{2}$

b

bottom



$\approx 173.1 \text{ GeV}/c^2$
 $\frac{2}{3}$
 $\frac{1}{2}$

t

top

And strange, bottom and top...

Standard Model of Elementary Particles

(and their anti-particles!)

three generations of matter (fermions)						interactions / force carriers (bosons)	
I		II		III			
mass	$\approx 2.2 \text{ MeV}/c^2$	$\approx 1.28 \text{ GeV}/c^2$	$\approx 173.1 \text{ GeV}/c^2$	0	$\approx 125.11 \text{ GeV}/c^2$		
charge	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0	0		
spin	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1	0		
QUARKS	u up	c charm	t top	g gluon	H higgs		
	$\approx 4.7 \text{ MeV}/c^2$	$\approx 96 \text{ MeV}/c^2$	$\approx 4.18 \text{ GeV}/c^2$	0			
	$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0			
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1			
	d down	s strange	b bottom	γ photon			
LEPTONS	$\approx 0.511 \text{ MeV}/c^2$	$\approx 105.66 \text{ MeV}/c^2$	$\approx 1.7768 \text{ GeV}/c^2$	$\approx 91.19 \text{ GeV}/c^2$			
	-1	-1	-1	0			
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1			
	e electron	μ muon	τ tau	Z Z boson			
	$< 1.0 \text{ eV}/c^2$	$< 0.17 \text{ MeV}/c^2$	$< 18.2 \text{ MeV}/c^2$	$\approx 80.360 \text{ GeV}/c^2$			
	0	0	0	± 1			
	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1			
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino	W W boson			

Dada! (etc...)