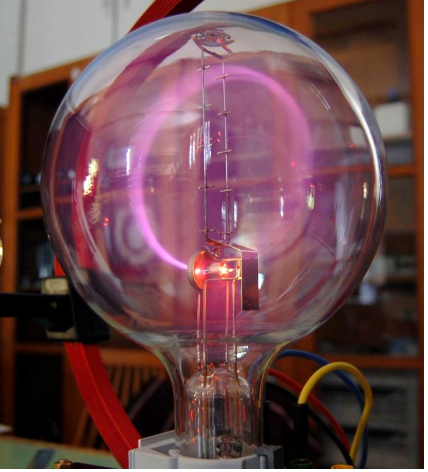
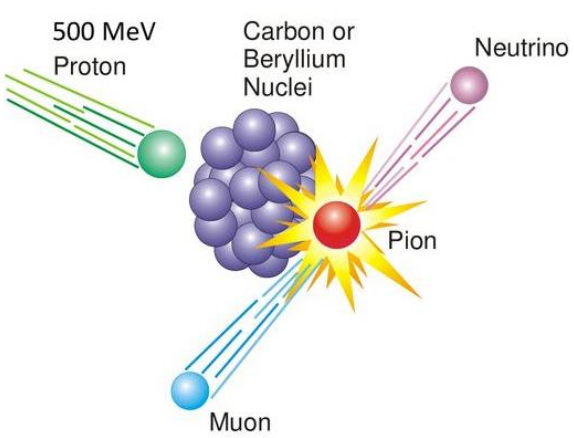
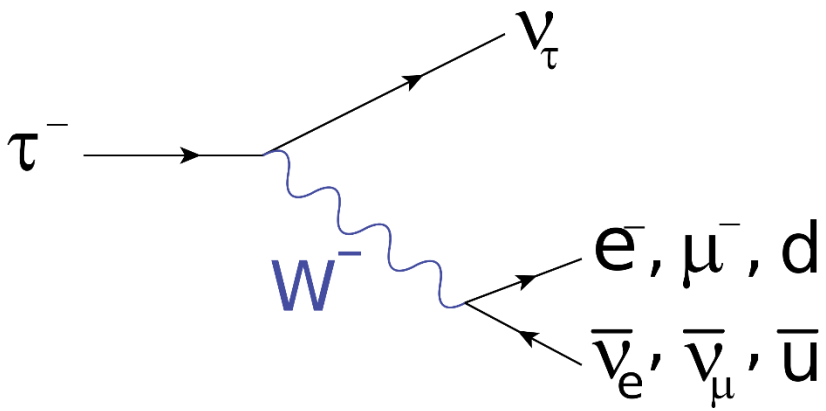




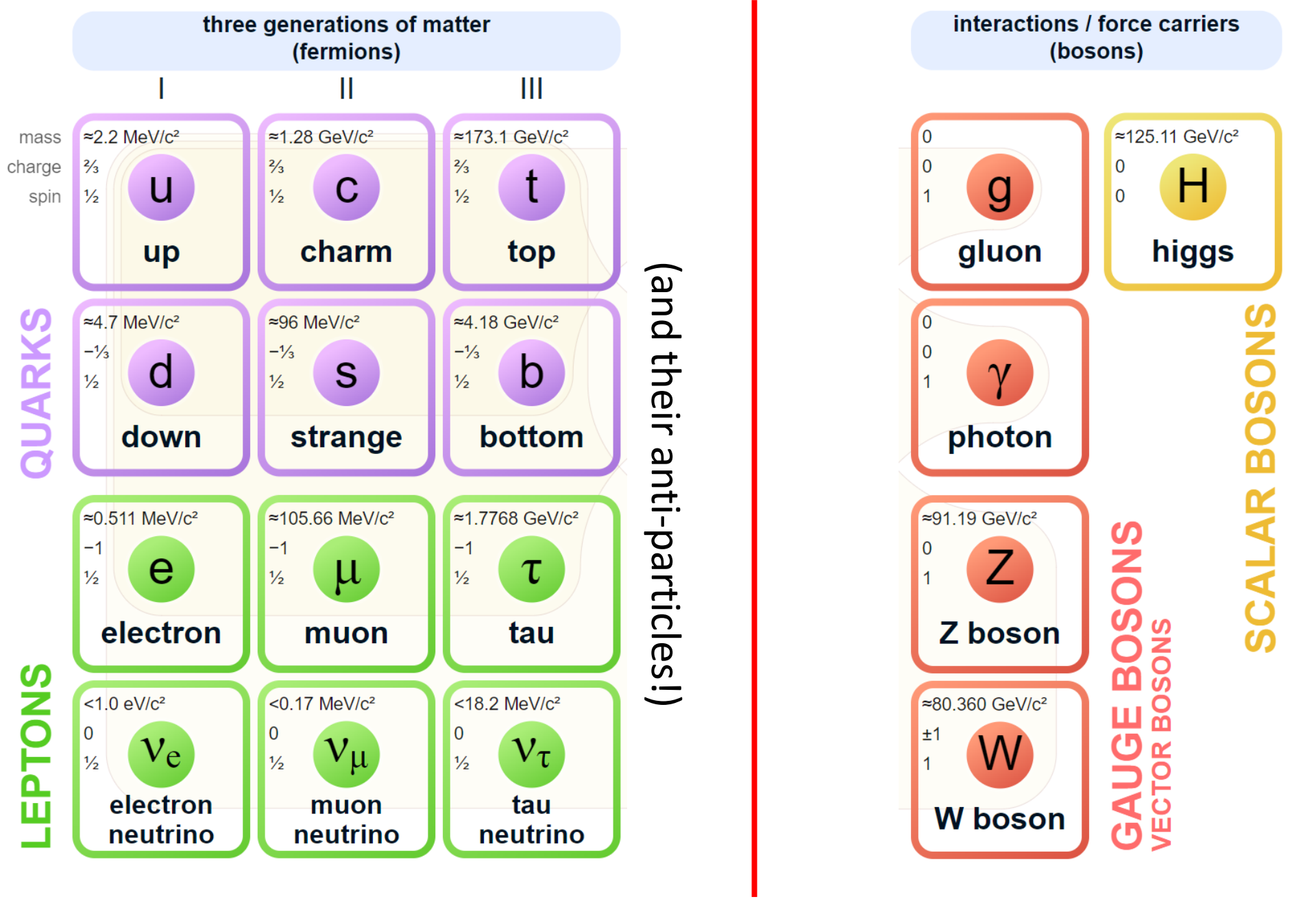


e μ and τ

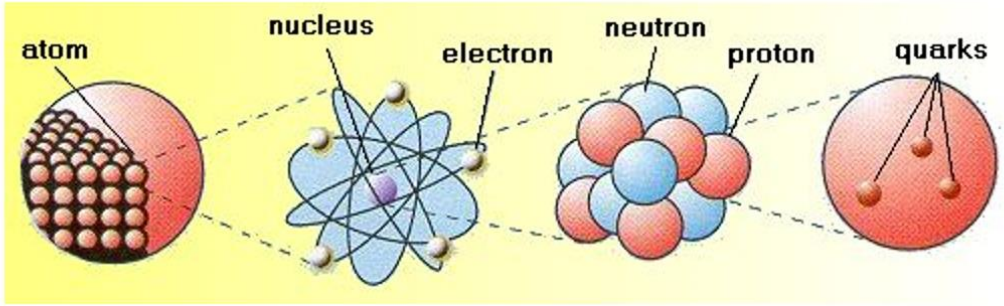
≈0.511 MeV/c²	≈105.66 MeV/c²	≈1.7768 GeV/c²
−1	−1	−1
½	½	½
e	μ	τ
electron	**muon**	**tau**

Andy "Dijon" French
March 2024

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



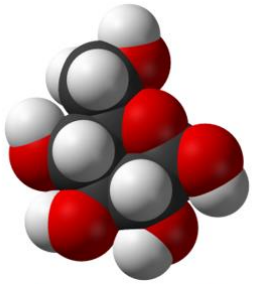
There are, two types of things



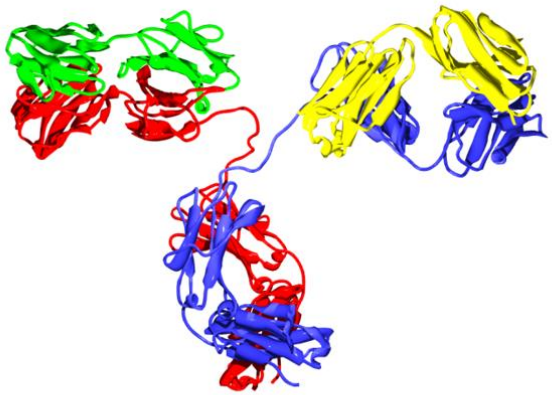
10^{-10} m

10^{-15} m

Glucose molecule

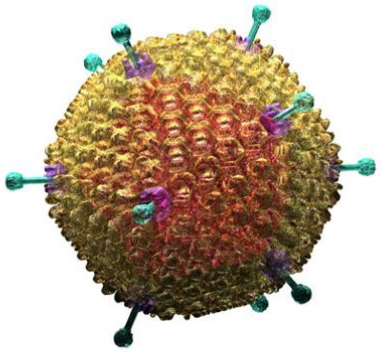


10^{-9} m



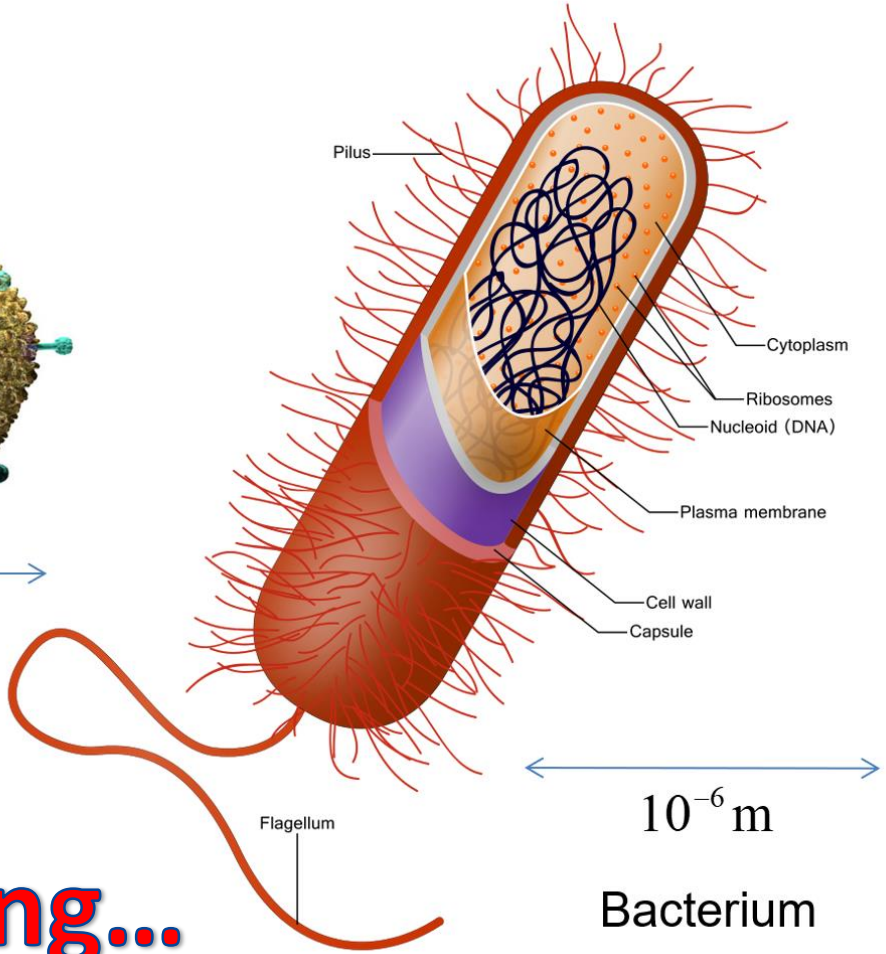
10^{-8} m

Antibody



10^{-7} m

Virus



10^{-6} m

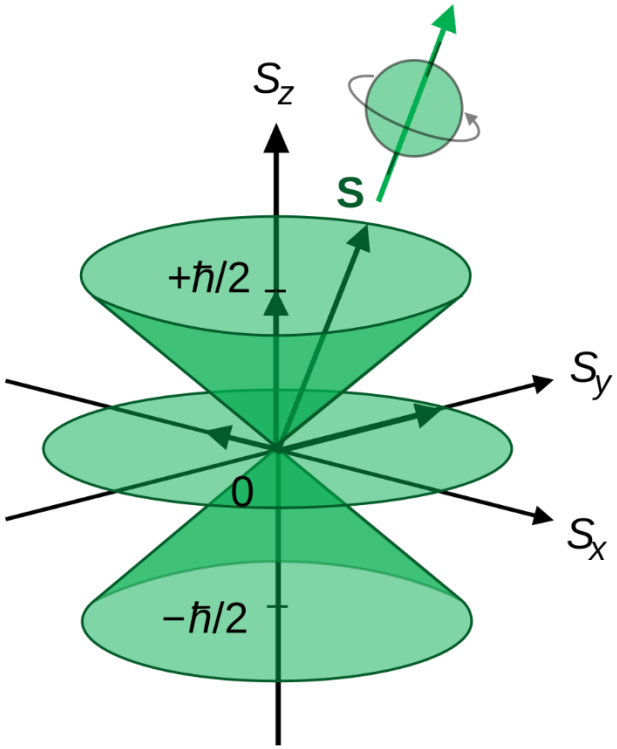
Bacterium

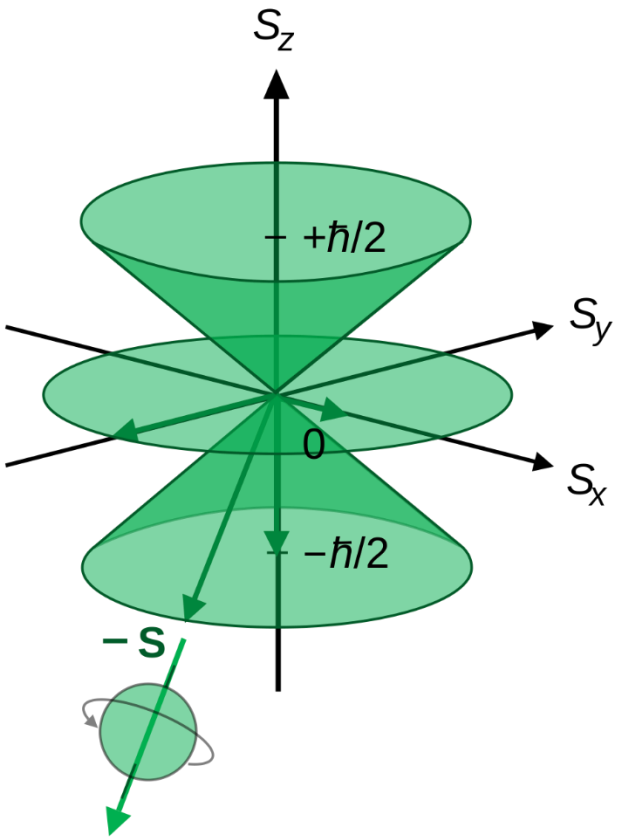
That make everything…


In the Universe

three generations of matter (fermions)

	I	II	III
mass	≈2.2 MeV/c²	≈1.28 GeV/c²	≈173.1 GeV/c²
charge	⅔	⅔	⅔
spin	½	½	½
QUARKS	u up	c charm	t top
	≈4.7 MeV/c²	≈96 MeV/c²	≈4.18 GeV/c²
	−⅓	−⅓	−⅓
	½	½	½
	d down	s strange	b bottom
LEPTONS	≈0.511 MeV/c²	≈105.66 MeV/c²	≈1.7768 GeV/c²
	−1	−1	−1
	½	½	½
	e electron	μ muon	τ tau
	<1.0 eV/c²	<0.17 MeV/c²	<18.2 MeV/c²
	0	0	0
	½	½	½
	ν_e electron neutrino	ν_μ muon neutrino	ν_τ tau neutrino





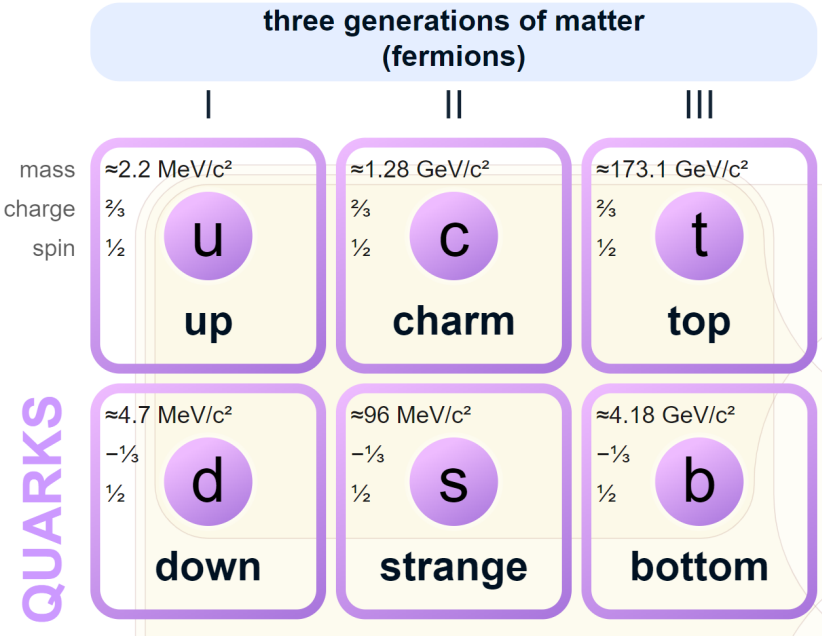
$$\left|\uparrow\right\rangle \equiv \left|+\frac{1}{2}\right\rangle$$

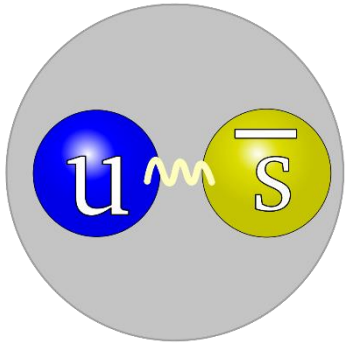
$$\left|\downarrow\right\rangle \equiv \left|-\frac{1}{2}\right\rangle$$

Enrico Fermi
(1901-1954)

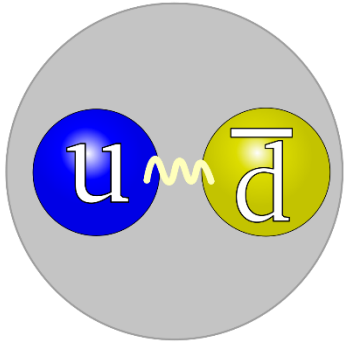
There's Fermions…

With half-integer spin yeah

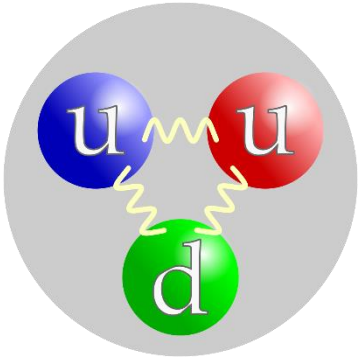




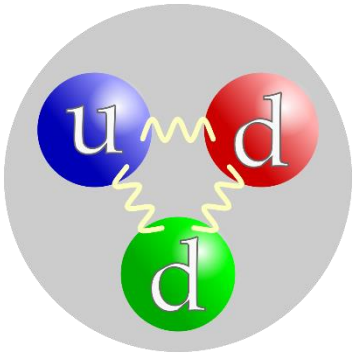
kaon (+)



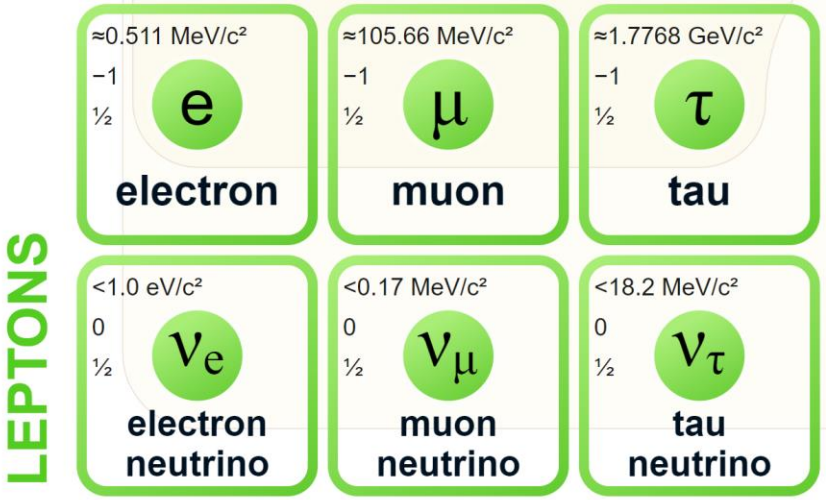
pion (+)



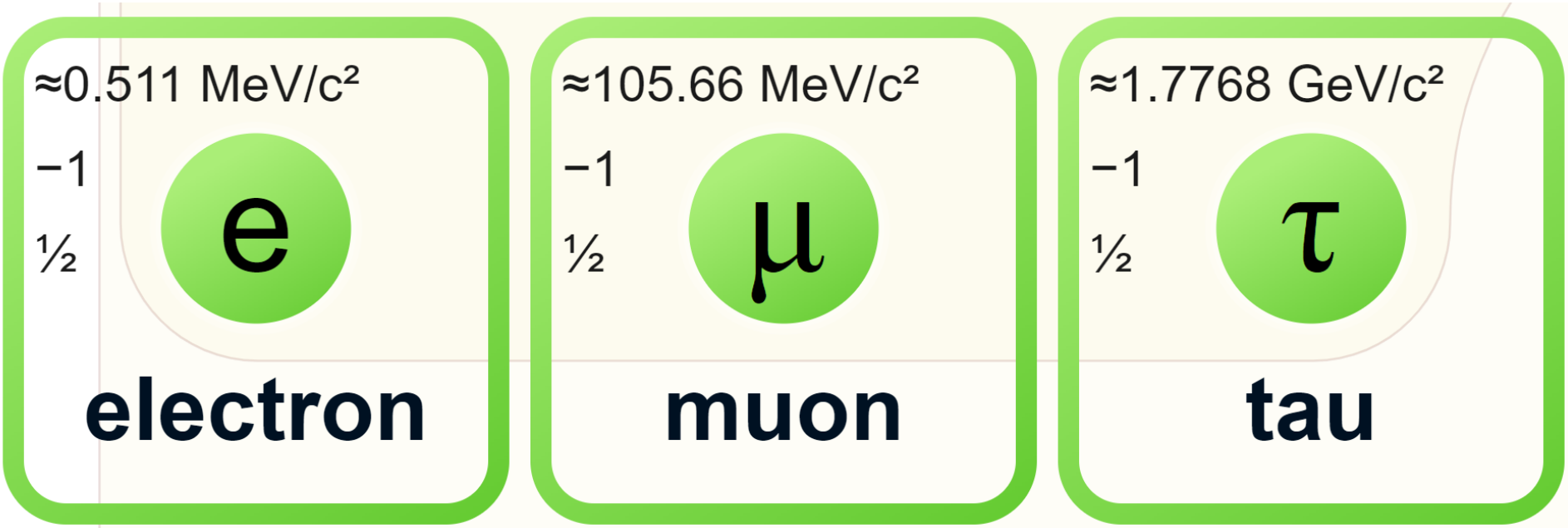
proton



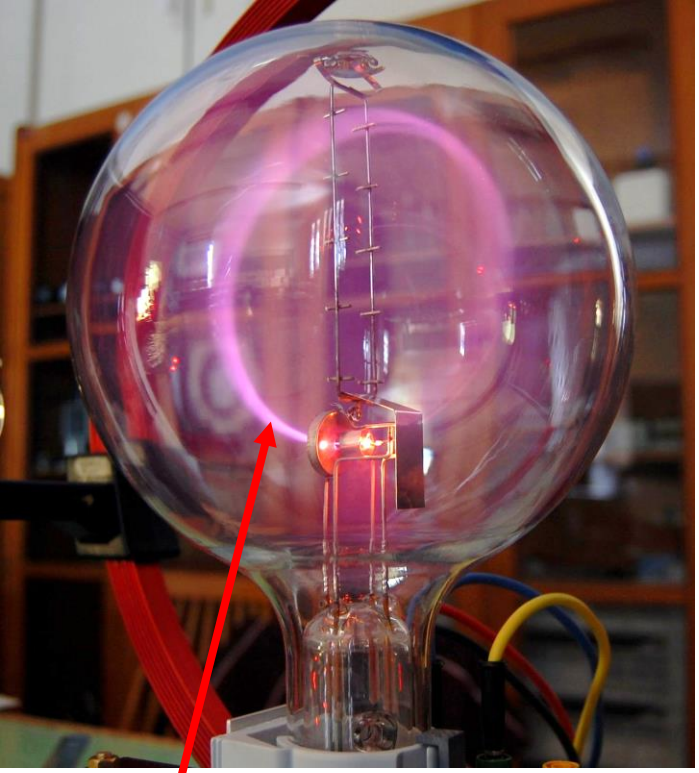
neutron



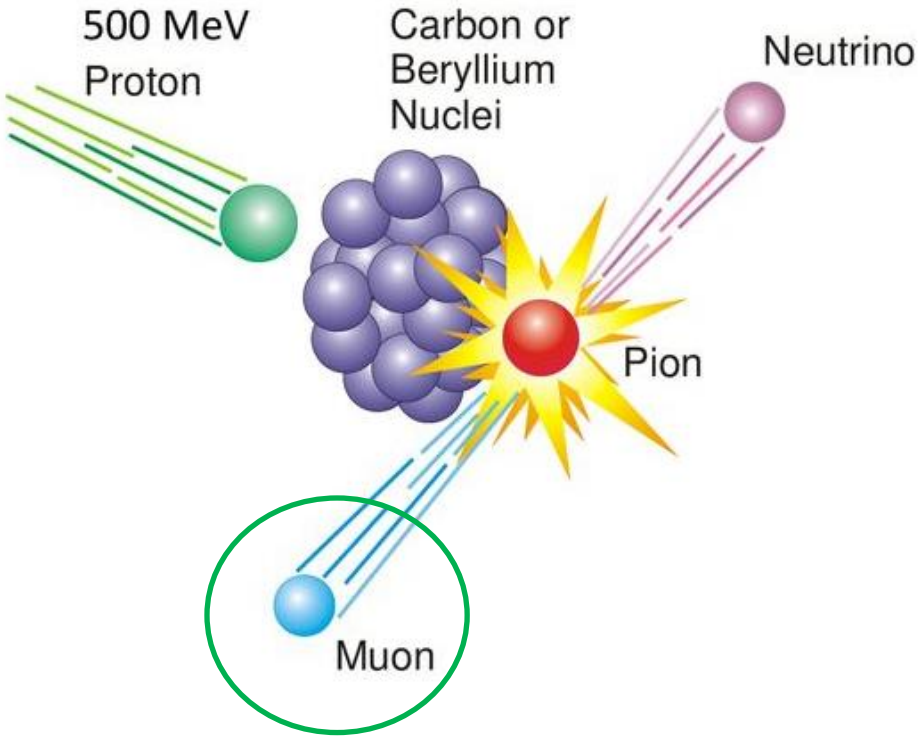
They're either groupings of quarks, or leptons

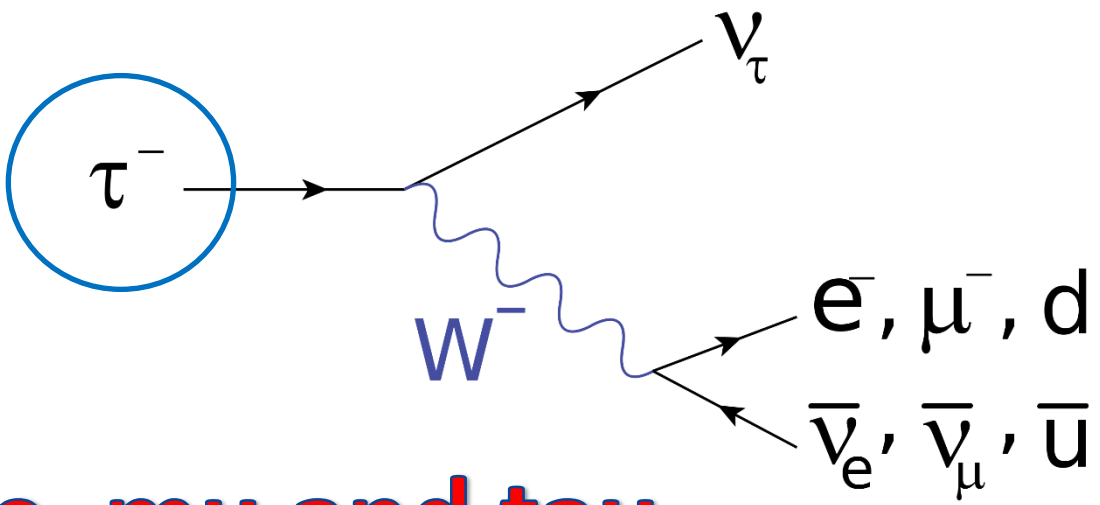


(such as) e, mu and tau

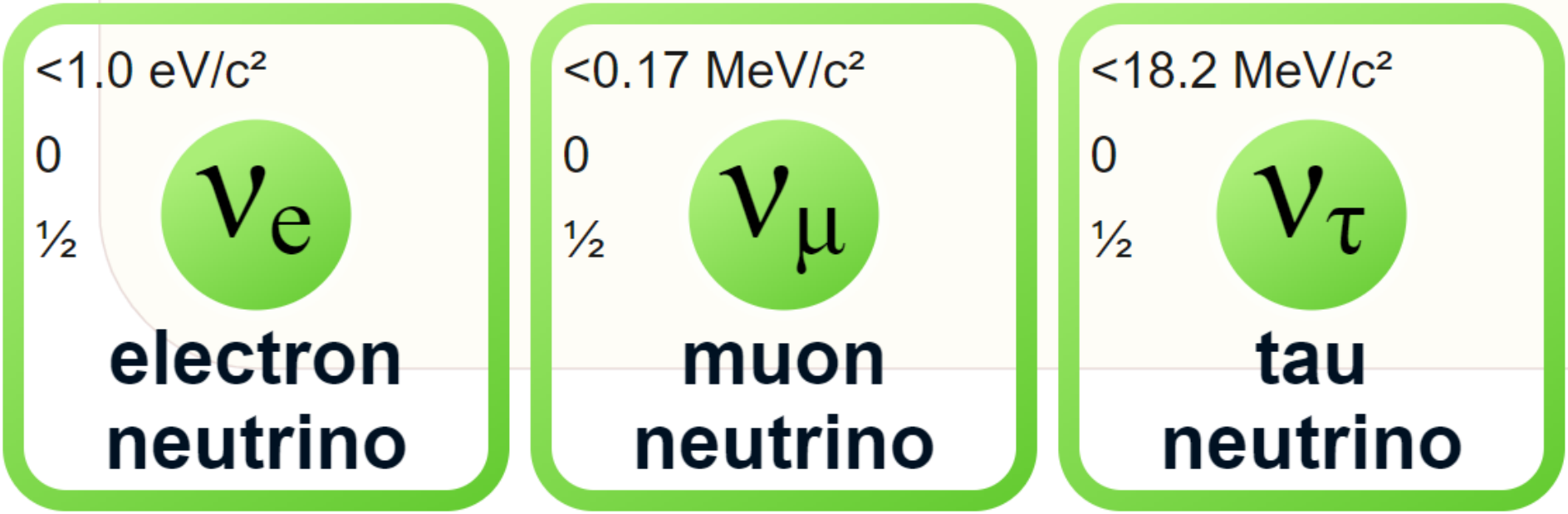


e^-


500 MeV
Proton
Carbon or
Beryllium
Nuclei
Neutrino
Pion
Muon

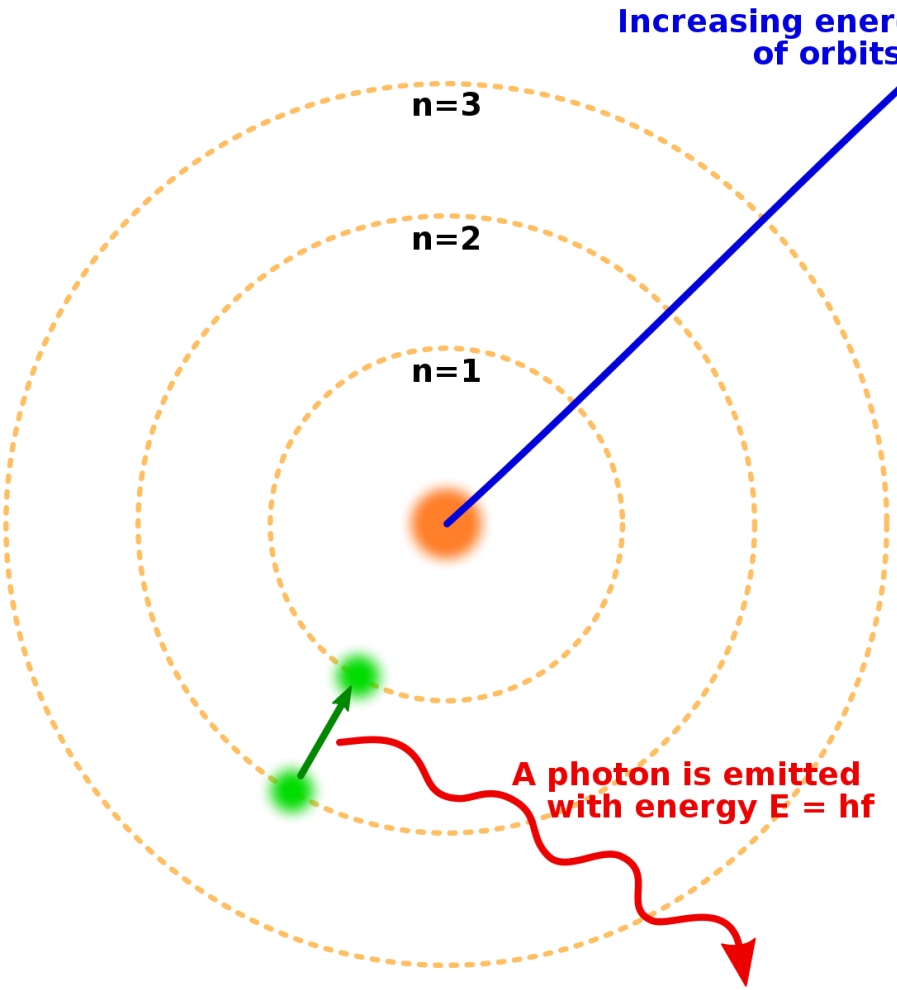

ν_τ
τ^-
W^-
e^-, μ^-, d
$\bar{\nu}_e, \bar{\nu}_\mu, \bar{u}$

e, mu and tau



(and their anti-particles!)

And their neutrinos, neutrinos!



e^-

An electron, already you will know

ELECTRON MASS

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

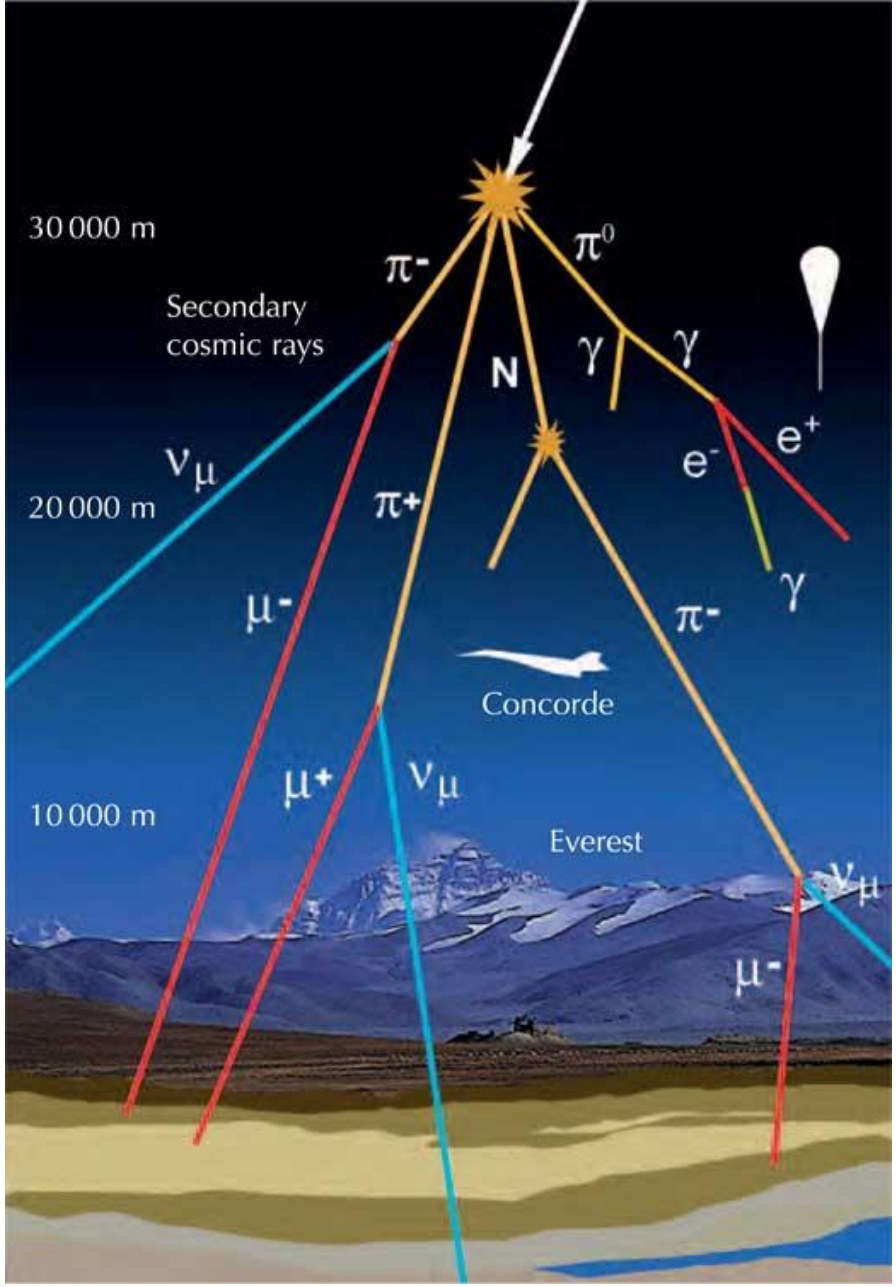
$$m_e = 0.511 \text{MeV}/\text{c}^2$$

Is pretty small

ELECTRON CHARGE

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

It's negatively charged



Muons made, from cosmic rays

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

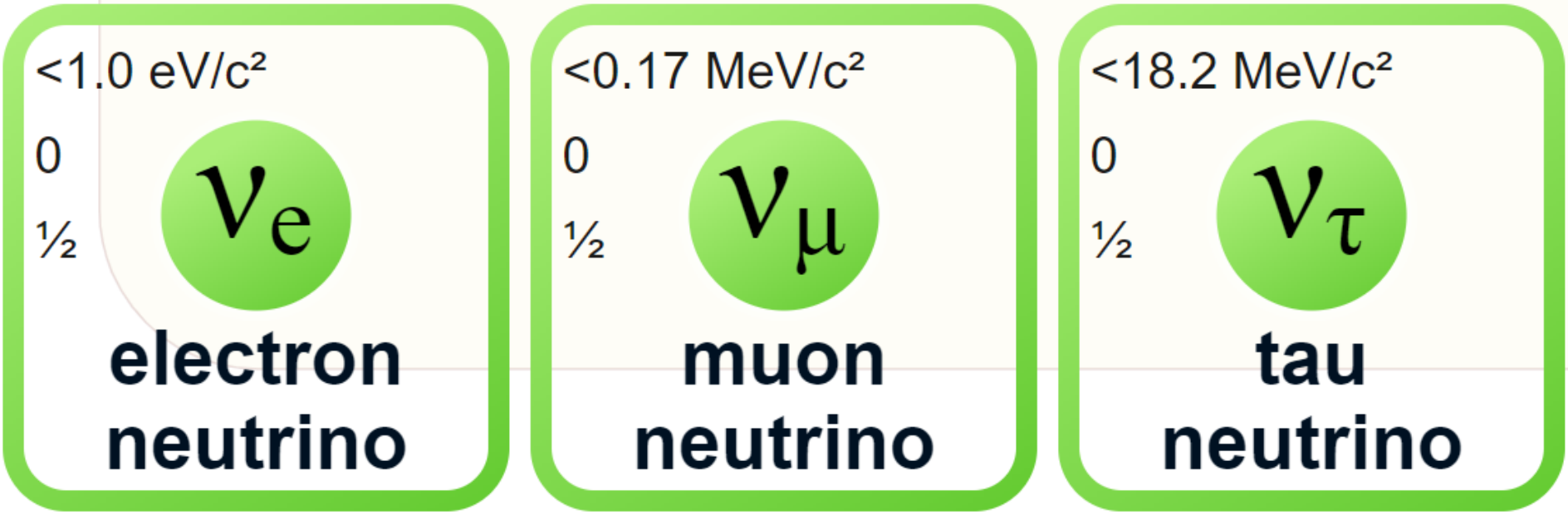
$$m_\mu \approx 206.77\, m_e$$

Two hundred times heavier

$$m_\mu \approx 206.77 m_e$$

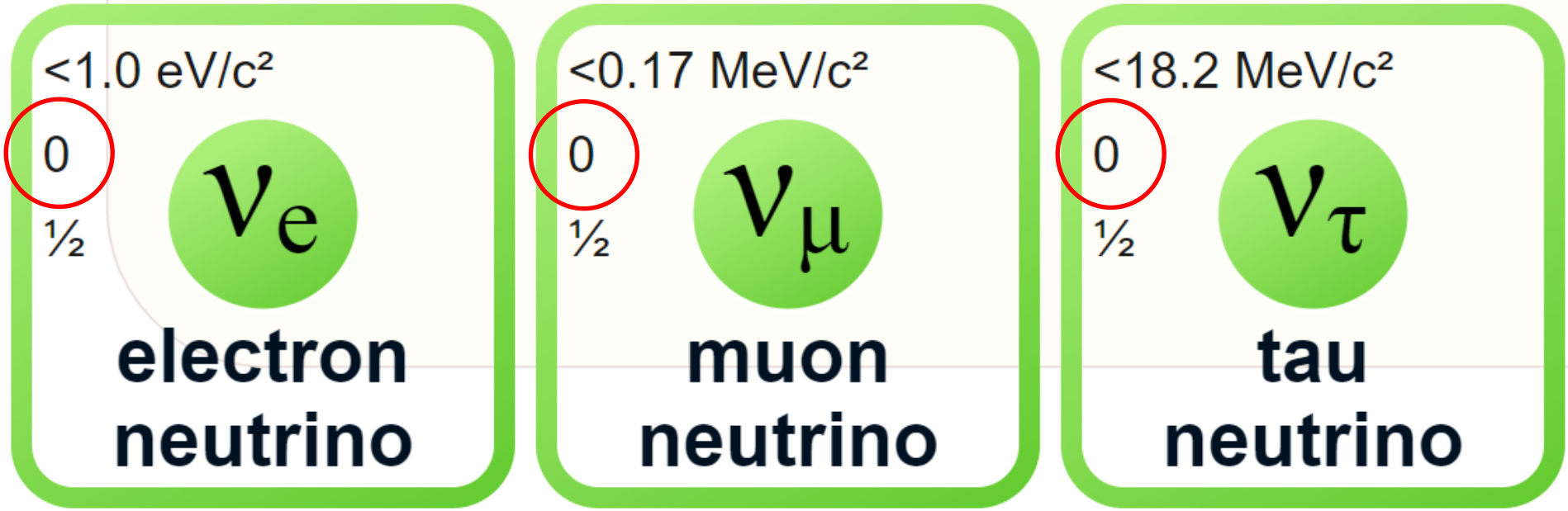
$$m_\tau \approx 17 m_\mu$$

And tau, tau, tau,
much more massive still



But what about neutrinos?

Wolfgang Pauli
(1900-1958)

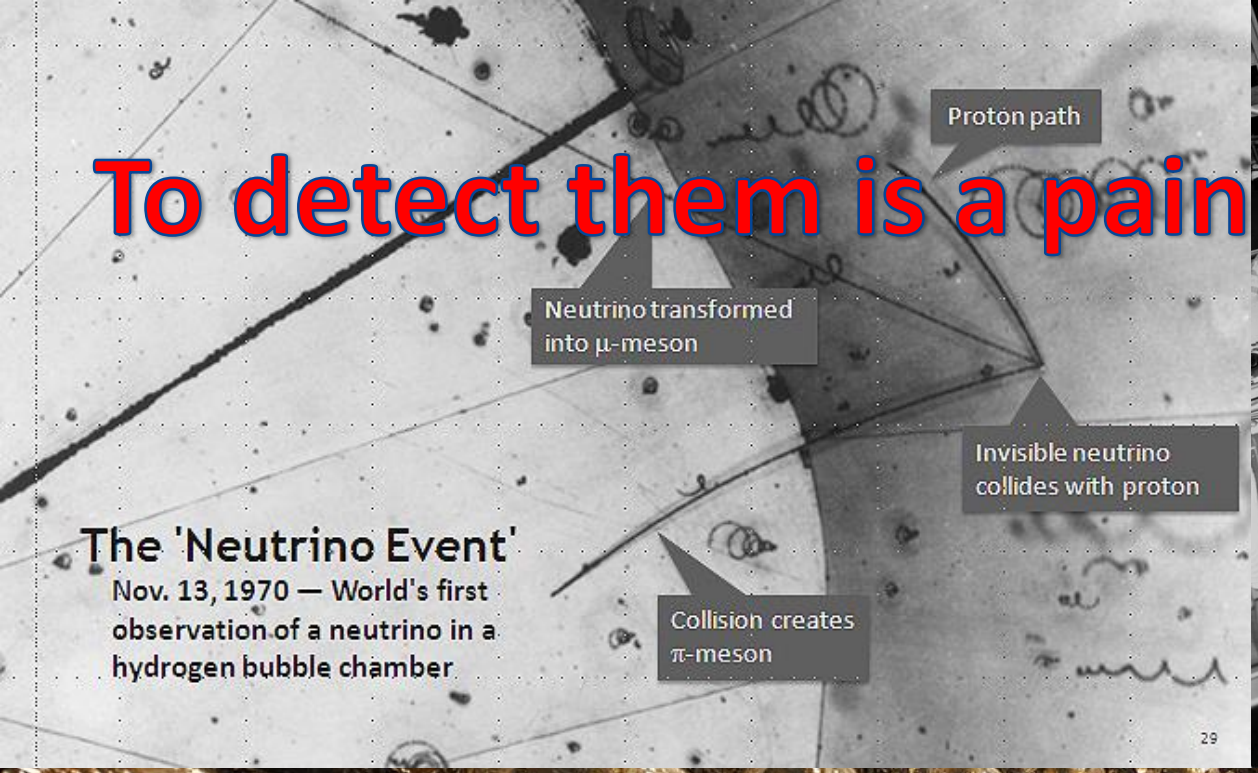


They don't have a charge

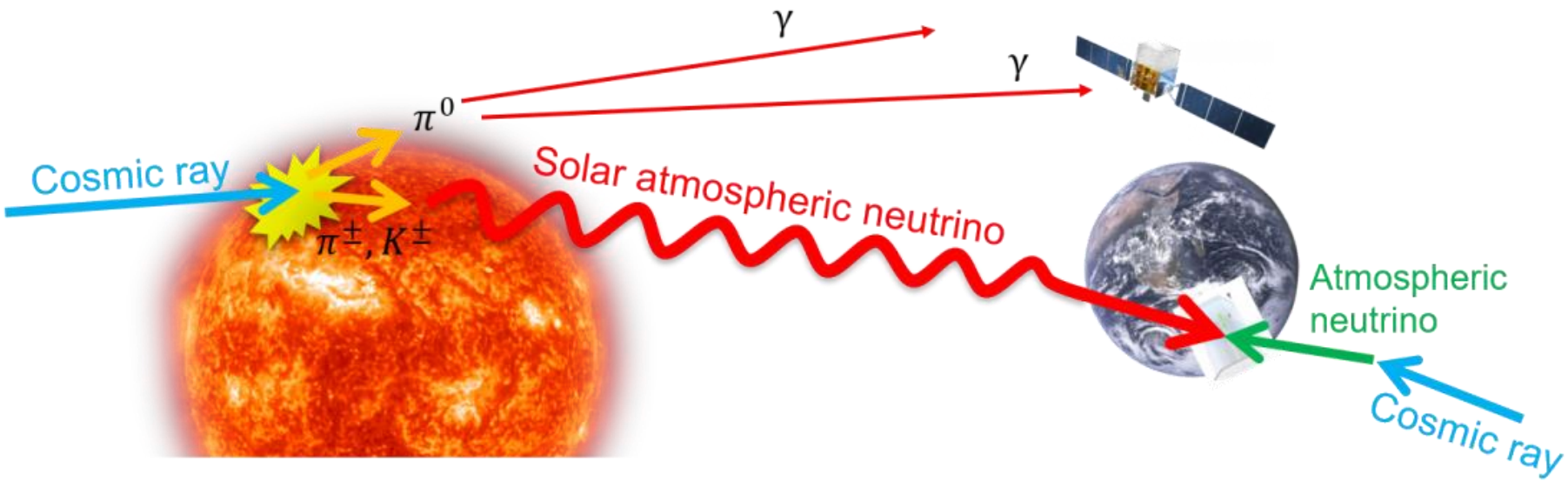
$$m_\nu < 2.14 \times 10^{-37}\,\mathrm{kg}$$

But might have a bit of mass

To detect them is a pain in the ass!

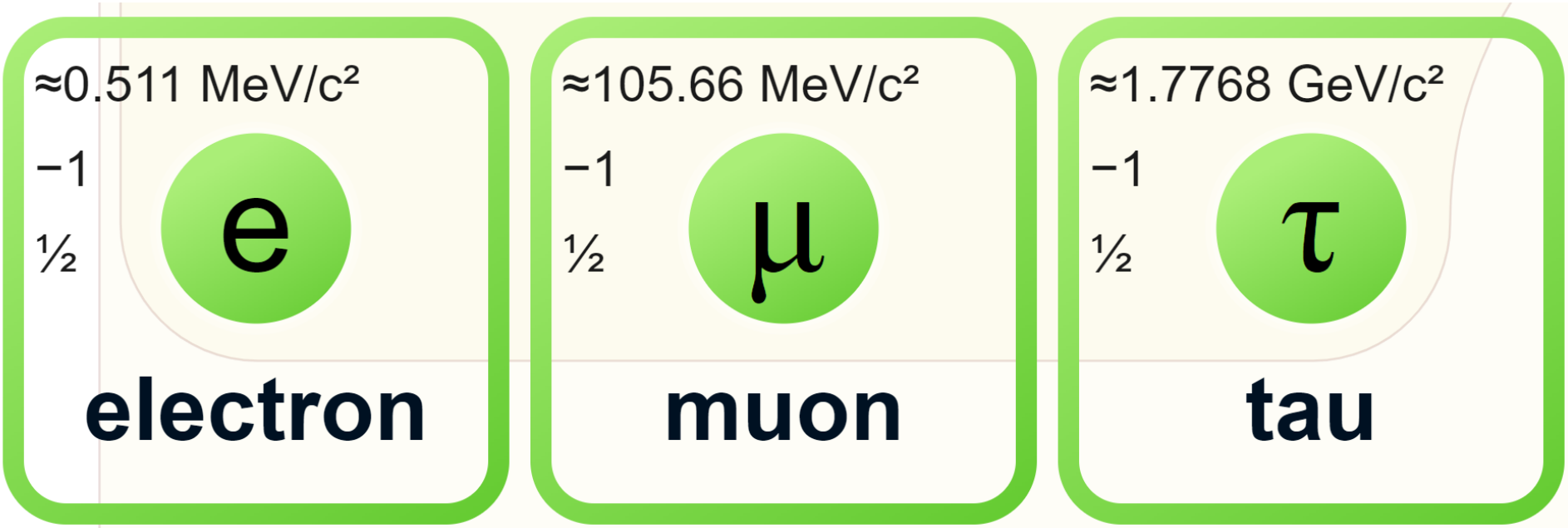


Reaction	Label	Flux $cm^{-1}s^{-1}$
$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$	pp	$5.95 \cdot 10^{10}$
$p + e^{-} + p \rightarrow {}^{2}H + \nu_e$	pep	$1.40 \cdot 10^{8}$
${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$	hep	$9.3 \cdot 10^{3}$
${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$	${}^{7}Be$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

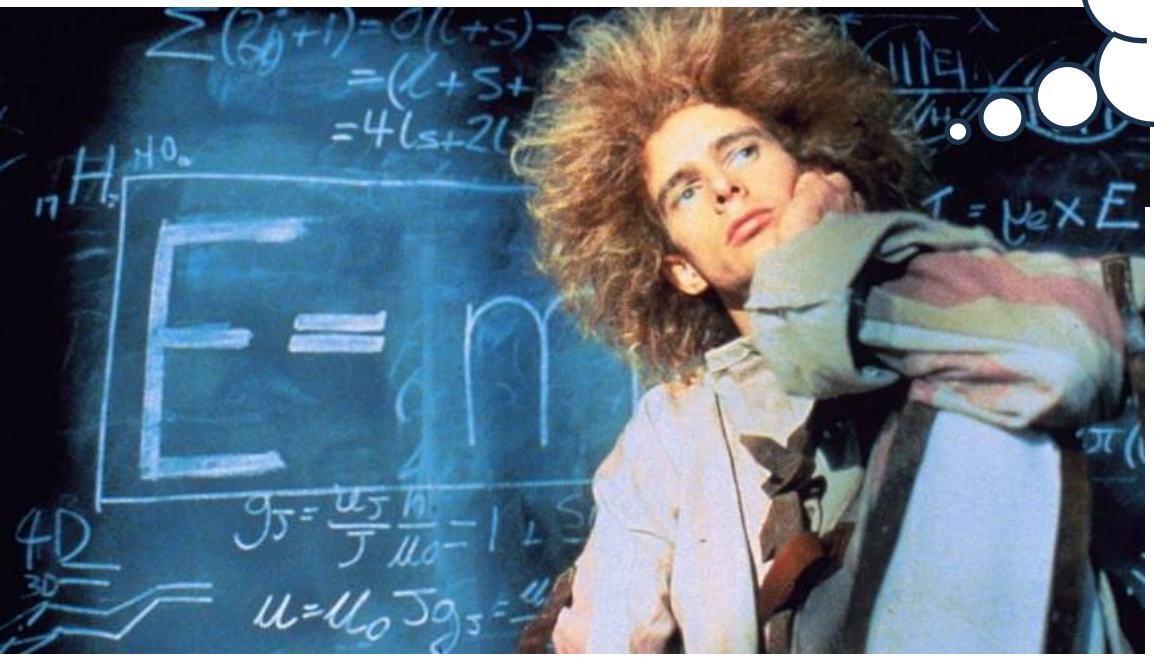


Trillions of them

are now passing through you


≈0.511 MeV/c²
−1
½
e
electron
≈105.66 MeV/c²
−1
½
μ
muon
≈1.7768 GeV/c²
−1
½
τ
tau

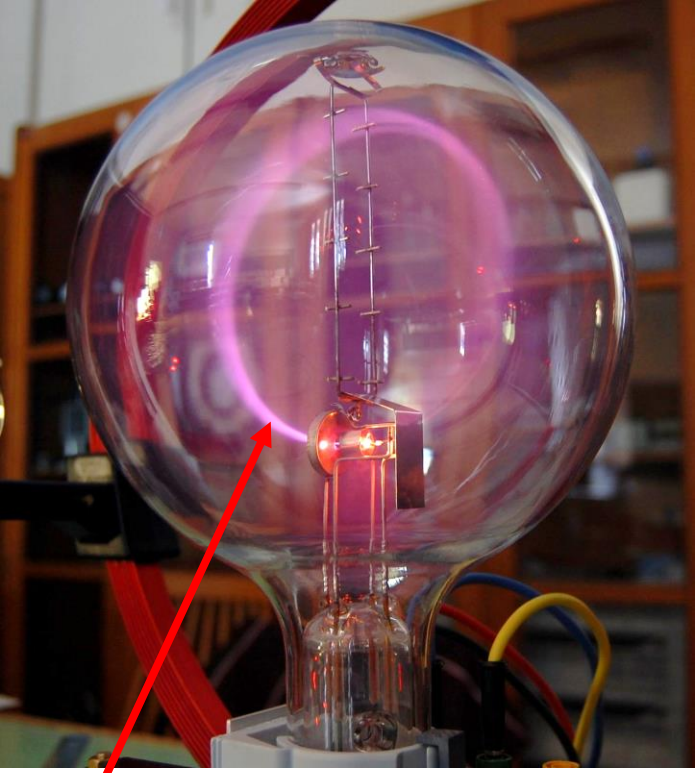
e, mu and tau



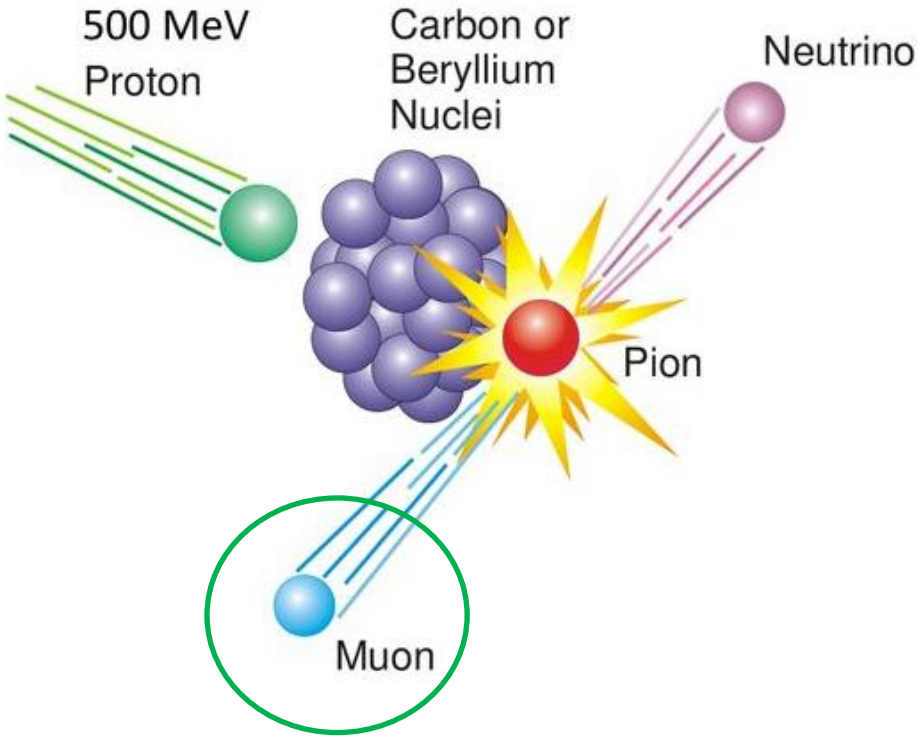
You can try, but it won't work!

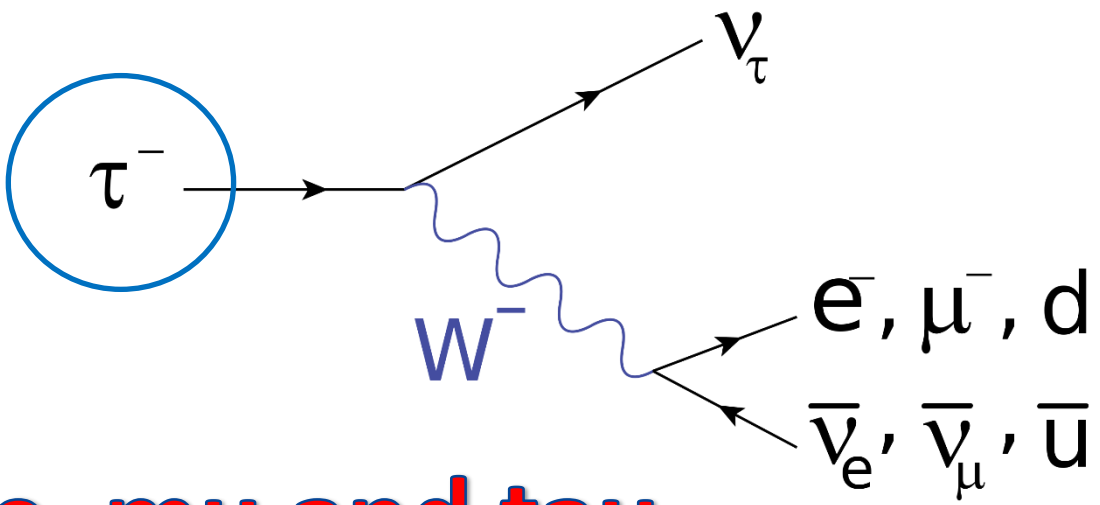
They're fundamental

can't split an electron

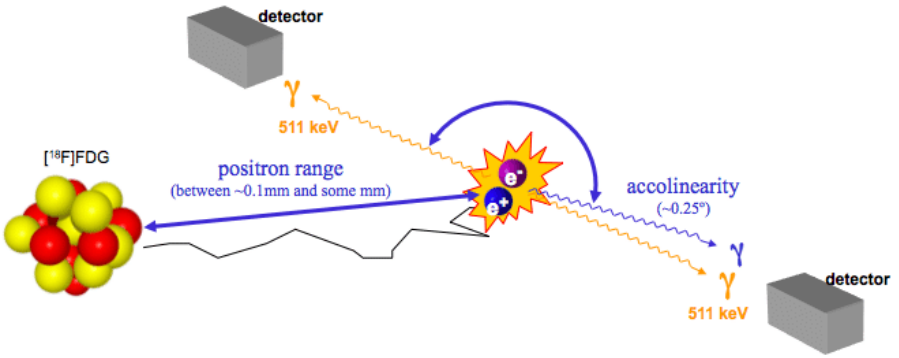


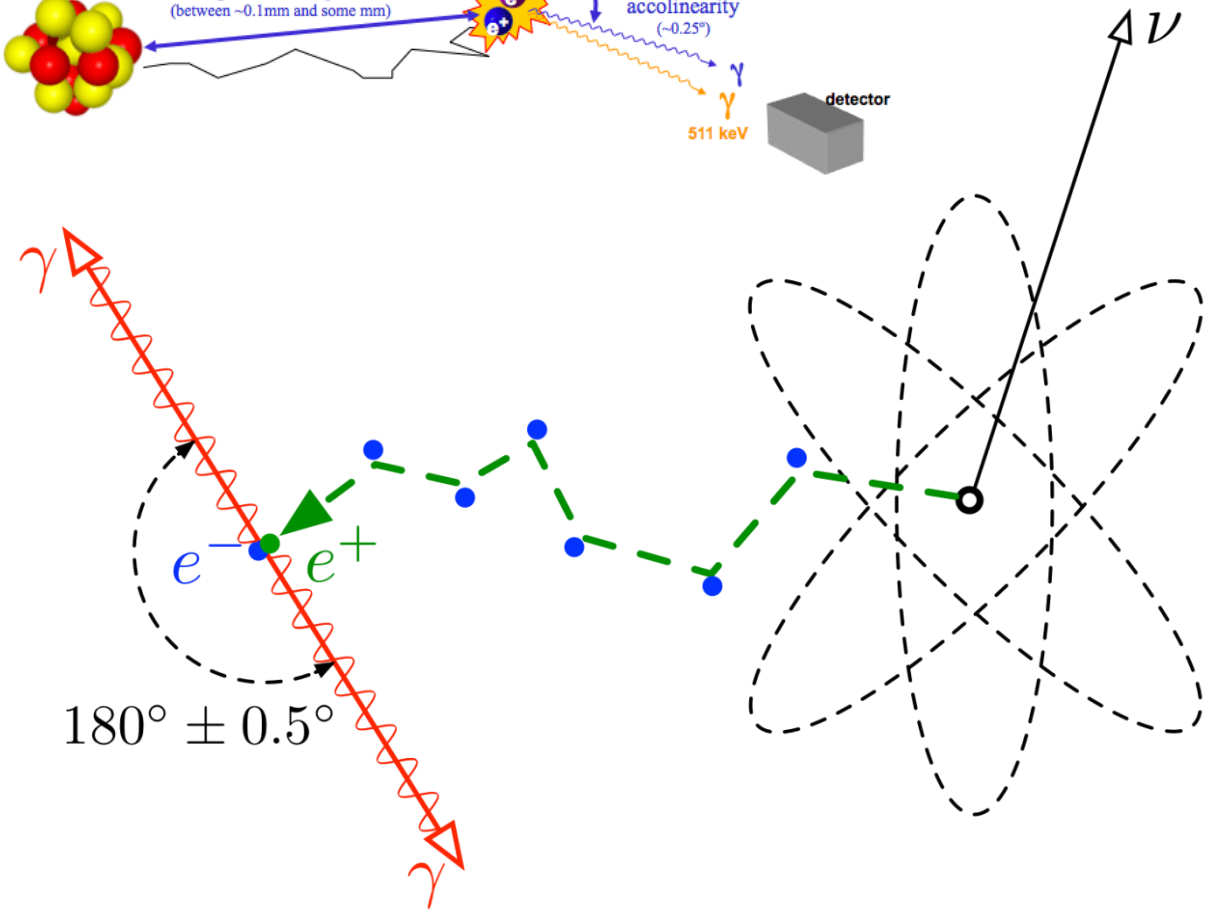
e^-


500 MeV
Proton
Carbon or
Beryllium
Nuclei
Neutrino
Pion
Muon


ν_τ
τ^-
W^-
e^-, μ^-, d
$\bar{\nu}_e, \bar{\nu}_\mu, \bar{u}$

e, mu and tau





e^+ positron

e^- electron

ν neutrino

γ quantum/photon (511 keV)

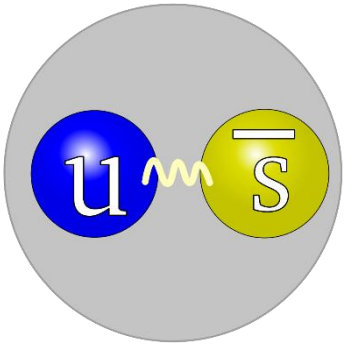
Add a positron and make two photons!

three generations of matter
(fermions)

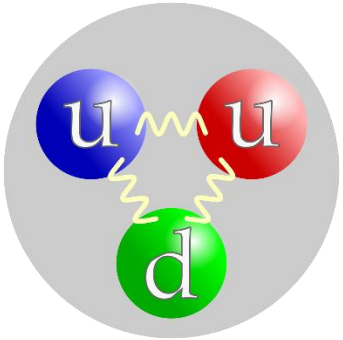
	I	II	III
mass	≈2.2 MeV/c²	≈1.28 GeV/c²	≈173.1 GeV/c²
charge	⅔	⅔	⅔
spin	½	½	½
QUARKS	u up	c charm	t top
	≈4.7 MeV/c²	≈96 MeV/c²	≈4.18 GeV/c²
	−⅓	−⅓	−⅓
	½	½	½
	d down	s strange	b bottom

Murray Gell-Mann
(1929-2019)

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



kaon (+)



proton

https://www.particlezoo.net/collections/quarks

≈2.2 MeV/c²

⅔

½

u

up

≈4.7 MeV/c²

−⅓

½

d

down

≈1.28 GeV/c²

⅔

½

c

charm

There's up, down and charm

≈96 MeV/c²

−⅓

½

s

strange

≈4.18 GeV/c²

−⅓

½

b

bottom

≈173.1 GeV/c²

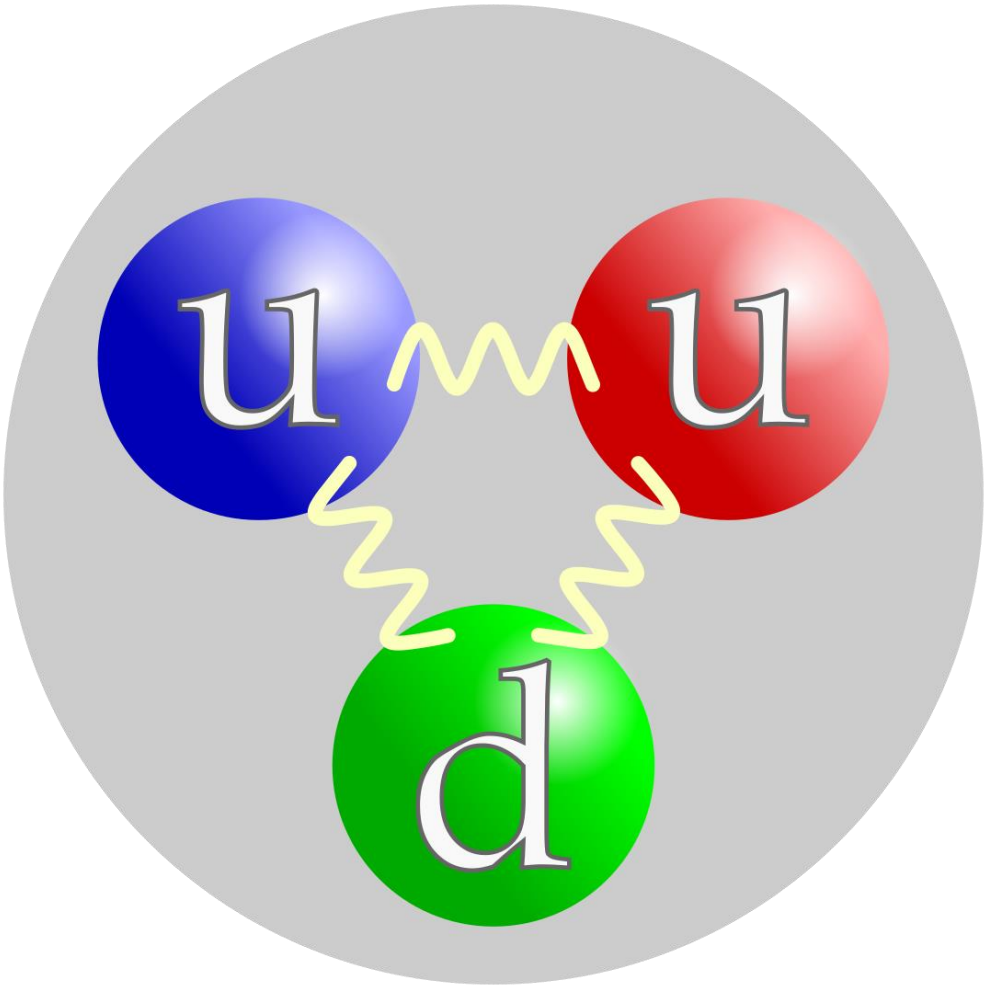
⅔

½

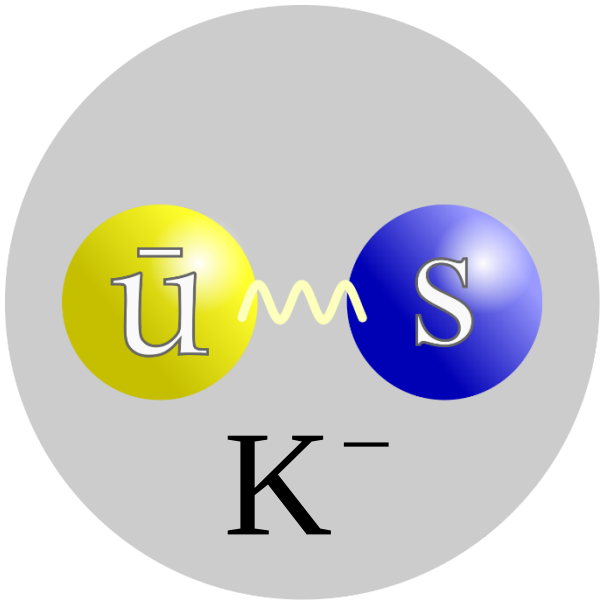
t

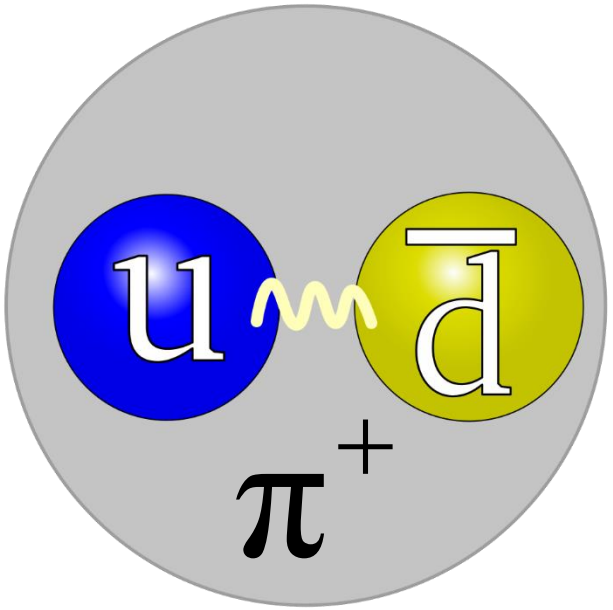
top

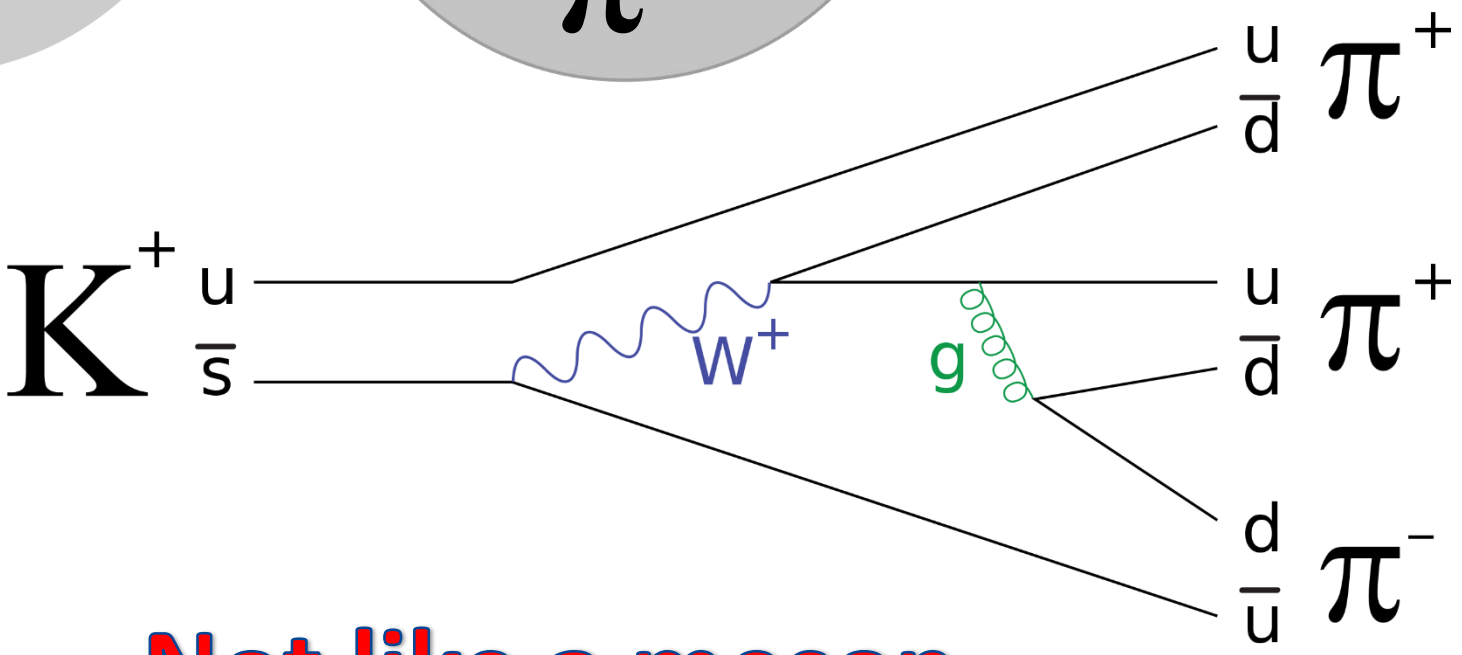
And strange, bottom and top…



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

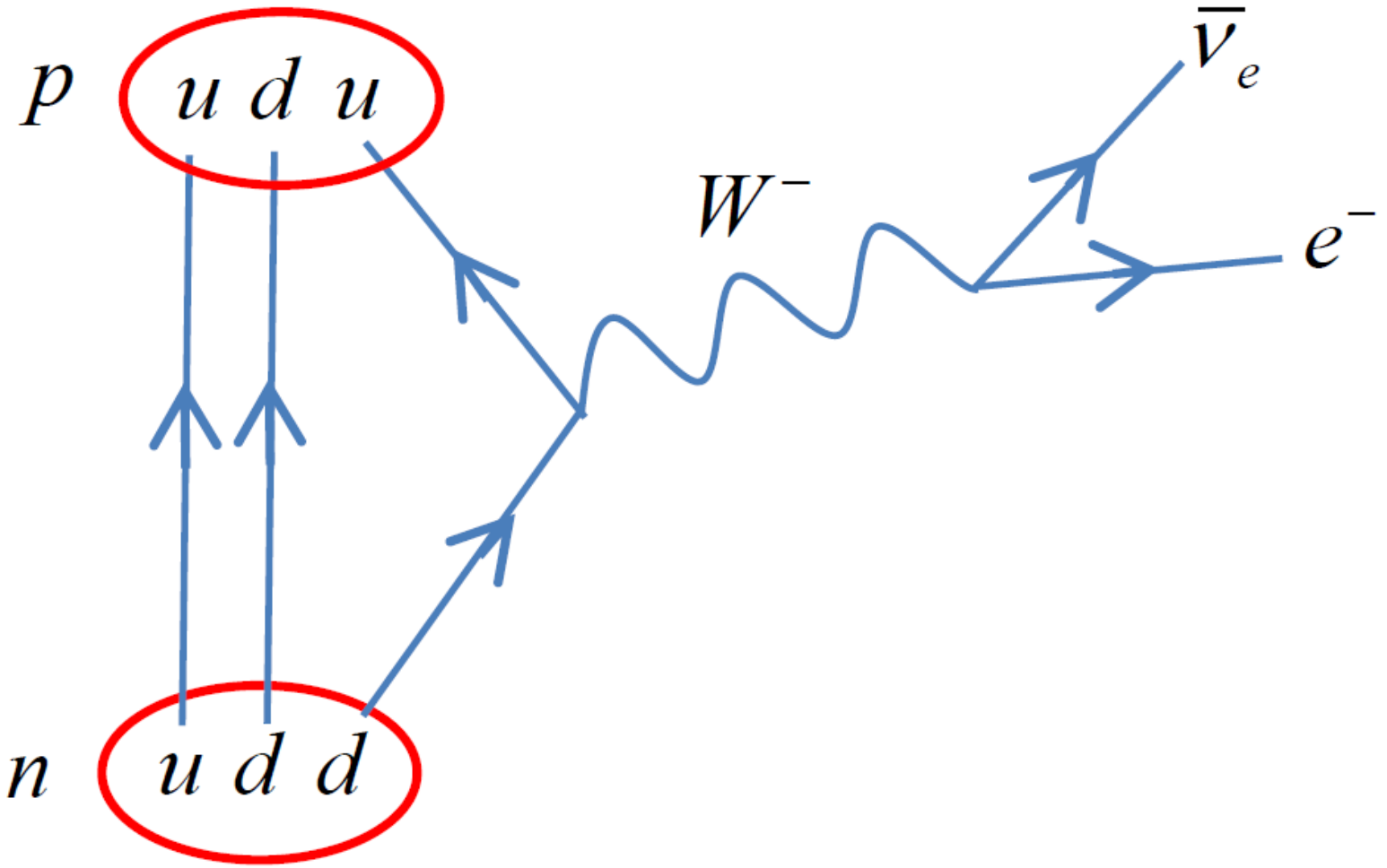






Not like a meson

(a quark and anti-quark pair)



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

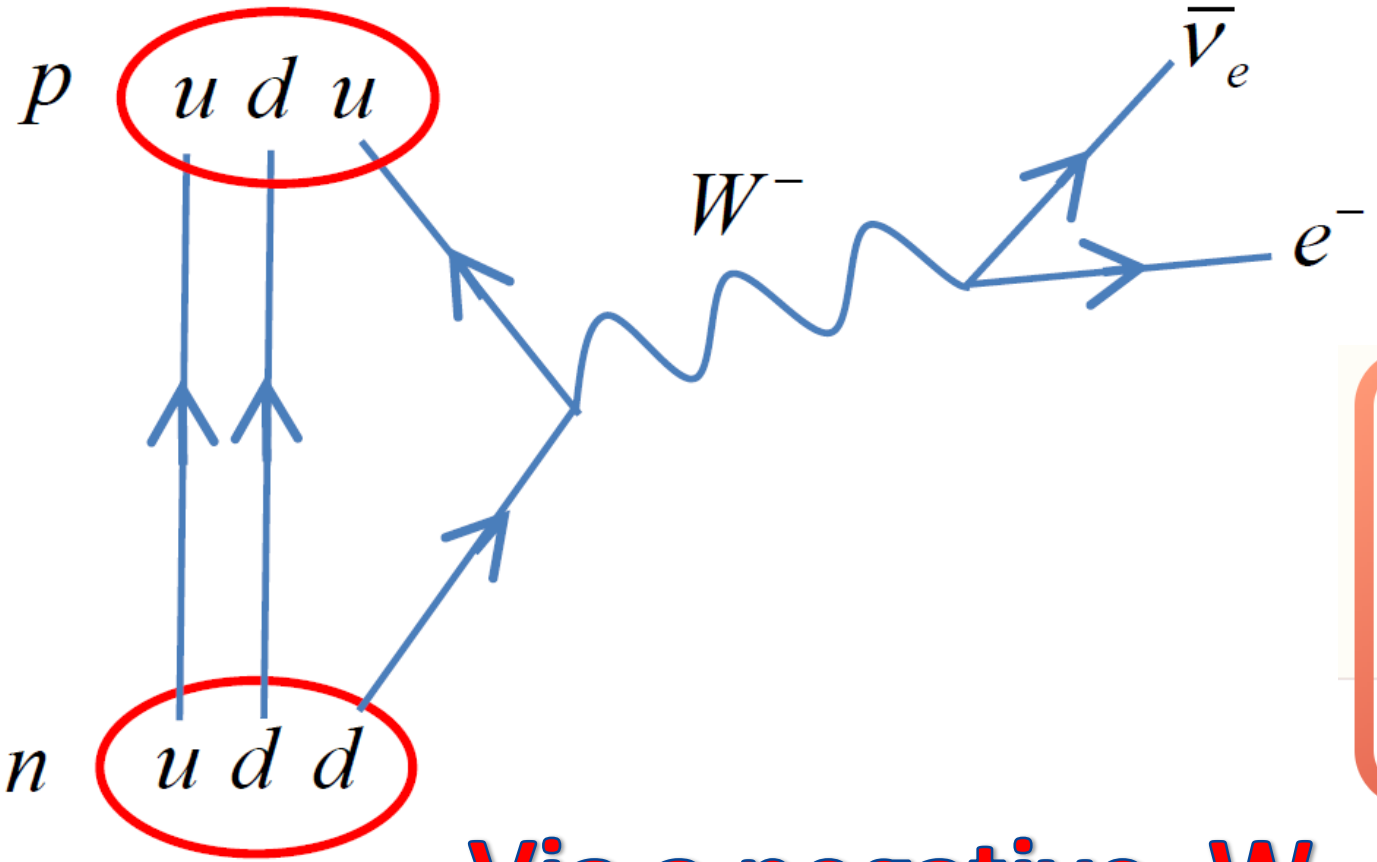
$$\Delta E \Delta t \geq \hbar$$
$$\Delta p \Delta x \geq \hbar$$

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

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

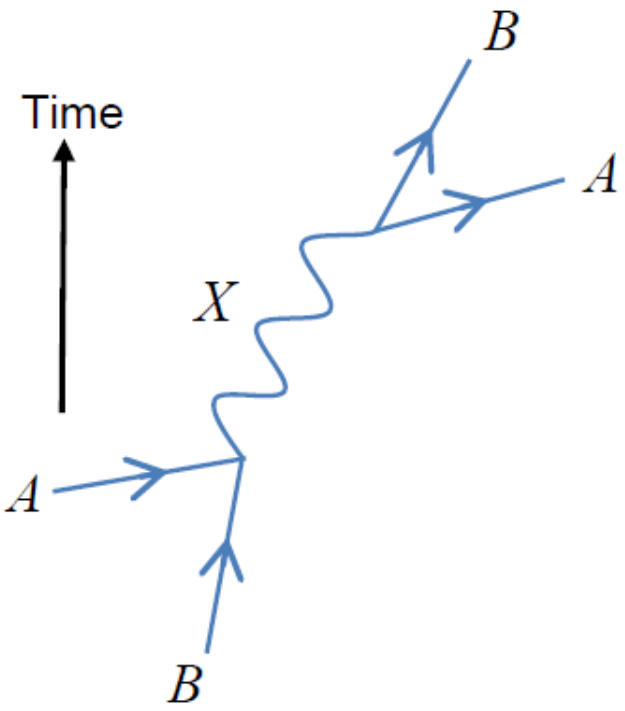
$$\therefore \Delta t \approx \frac{\hbar}{m_X c^2} = 8.19 \times 10^{-27}\,\text{s}$$ i.e. a very small time!

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

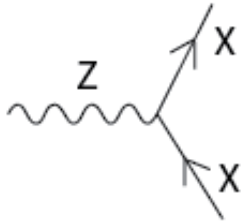


≈80.360 GeV/c²
±1
1
W
W boson

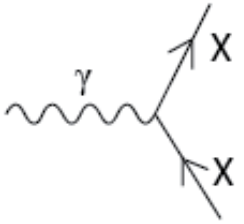
Via a negative, W



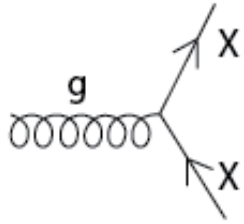
Standard Model Interactions
(Forces Mediated by Gauge Bosons)



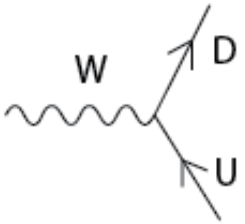
X is any fermion in the Standard Model.



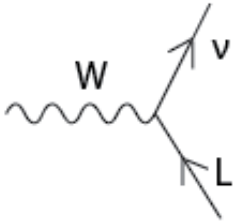
X is electrically charged.



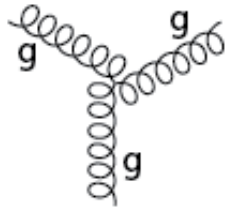
X is any quark.

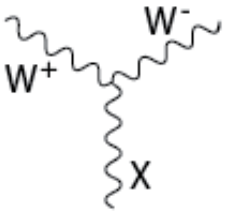


U is a up-type quark; D is a down-type quark.

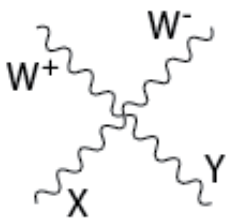


L is a lepton and ν is the corresponding neutrino.

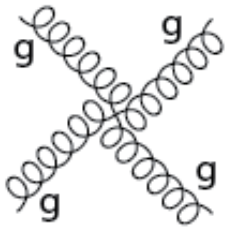




X is a photon or Z-boson.



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



How do these particles interact?

(via) Bosons

SCALAR BOSONS

≈125.11 GeV/c²
0
0
H
higgs

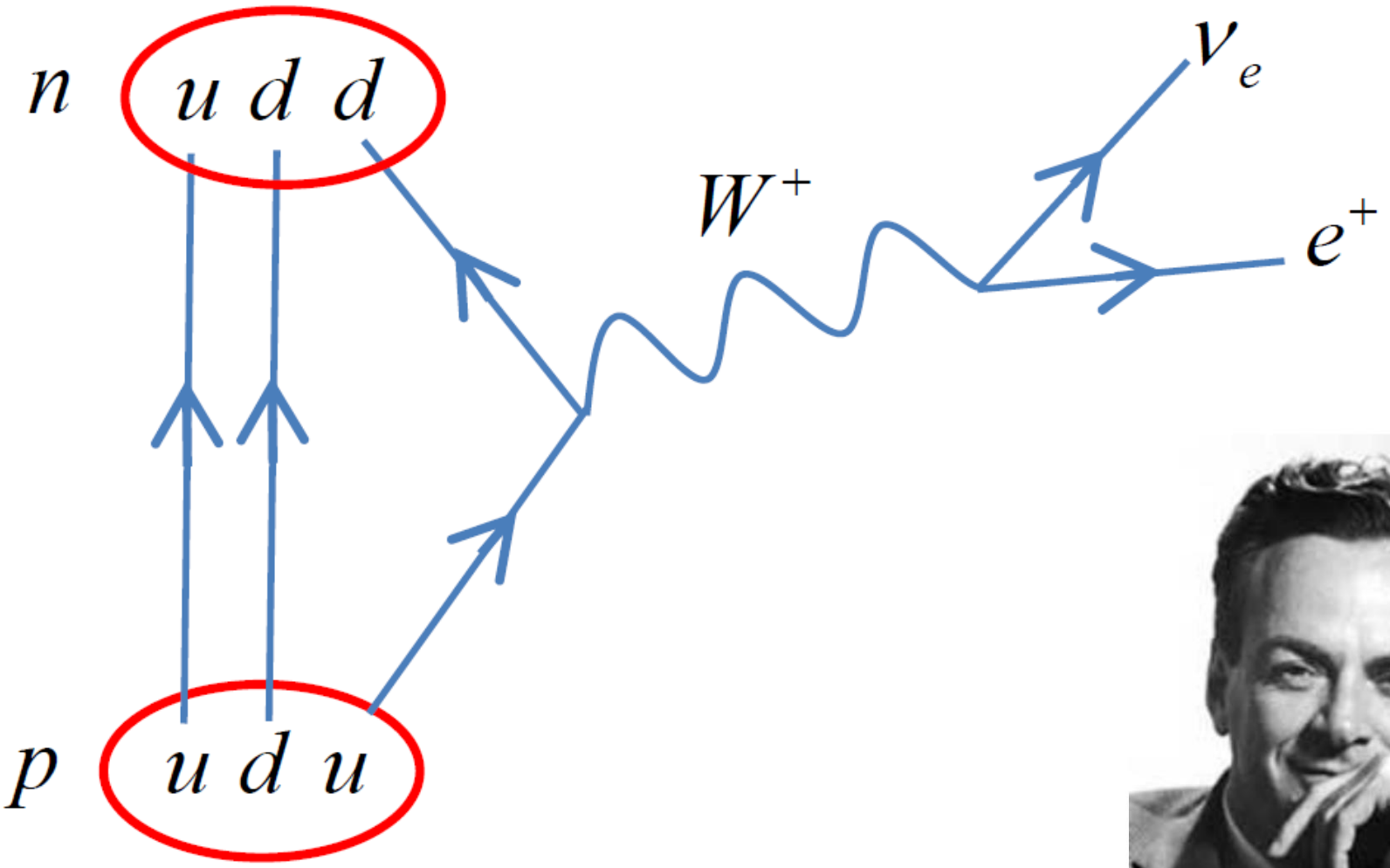
0
0
1
g
gluon

0
0
1
γ
photon

GAUGE BOSONS
VECTOR BOSONS

≈91.19 GeV/c²
0
1
Z
Z boson

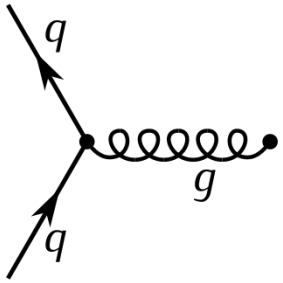
≈80.360 GeV/c²
±1
1
W
W boson

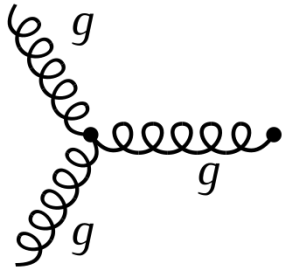


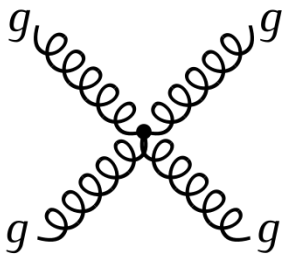
In a Feynman diagram

Richard Feynman
(1918-1988)

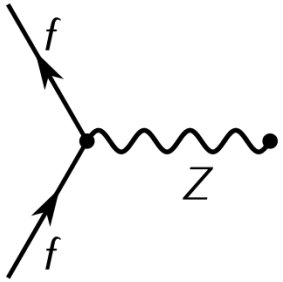
STRONG VERTICES

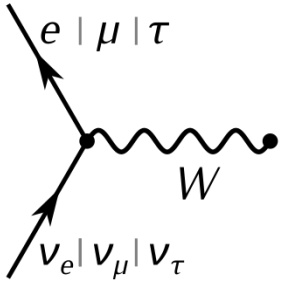


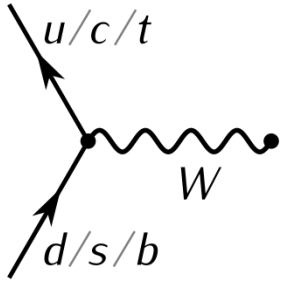




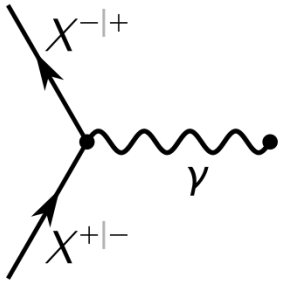
WEAK VERTICES



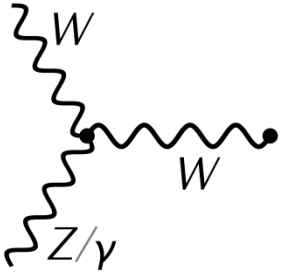


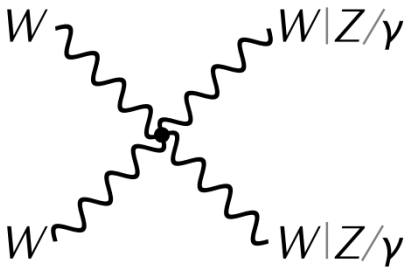


ELECTROMAGNETIC VERTEX

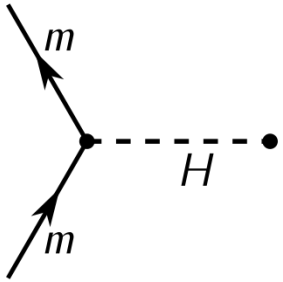


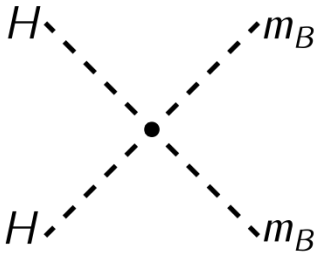
ELECTROWEAK VERTICES



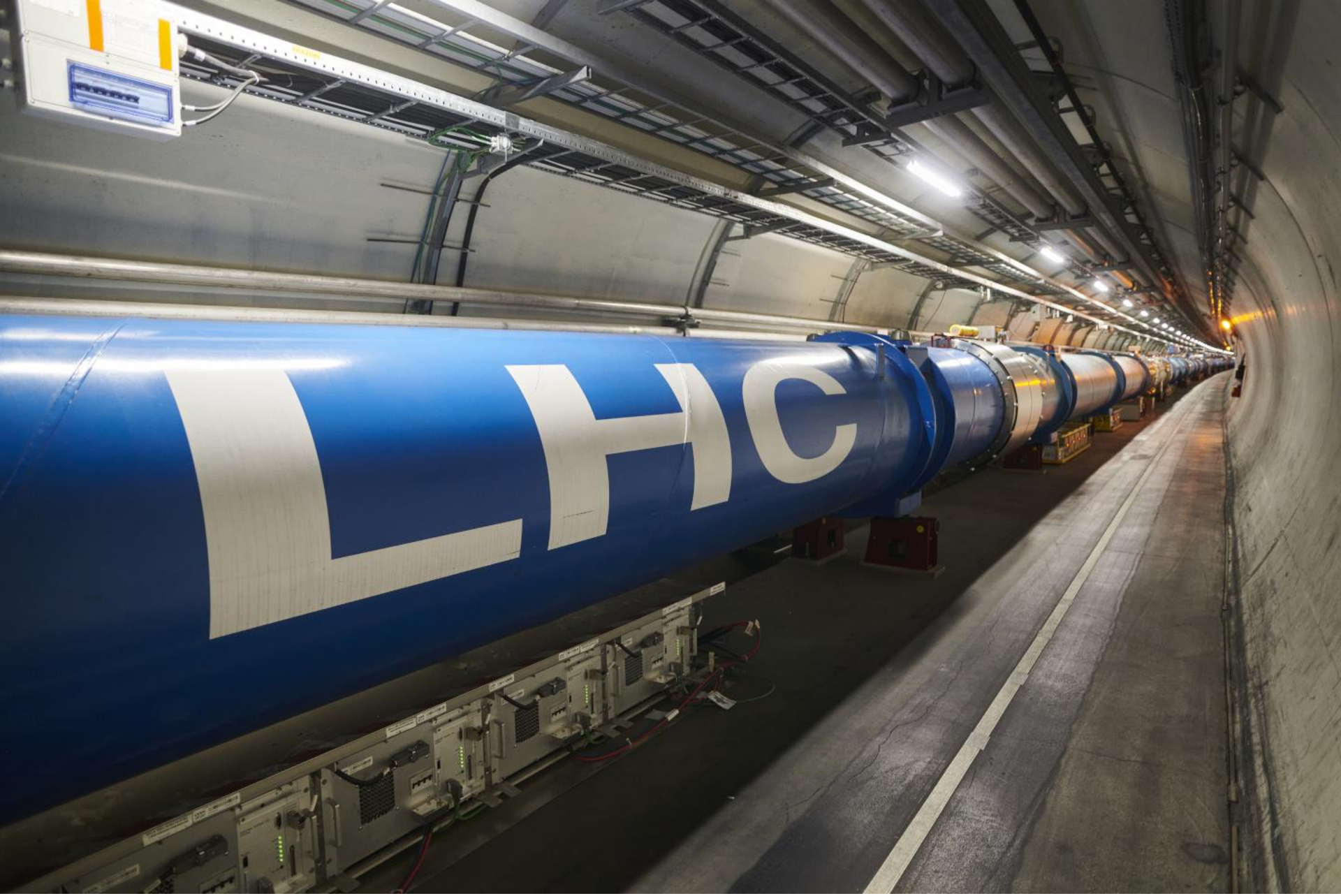


HIGGS VERTICES

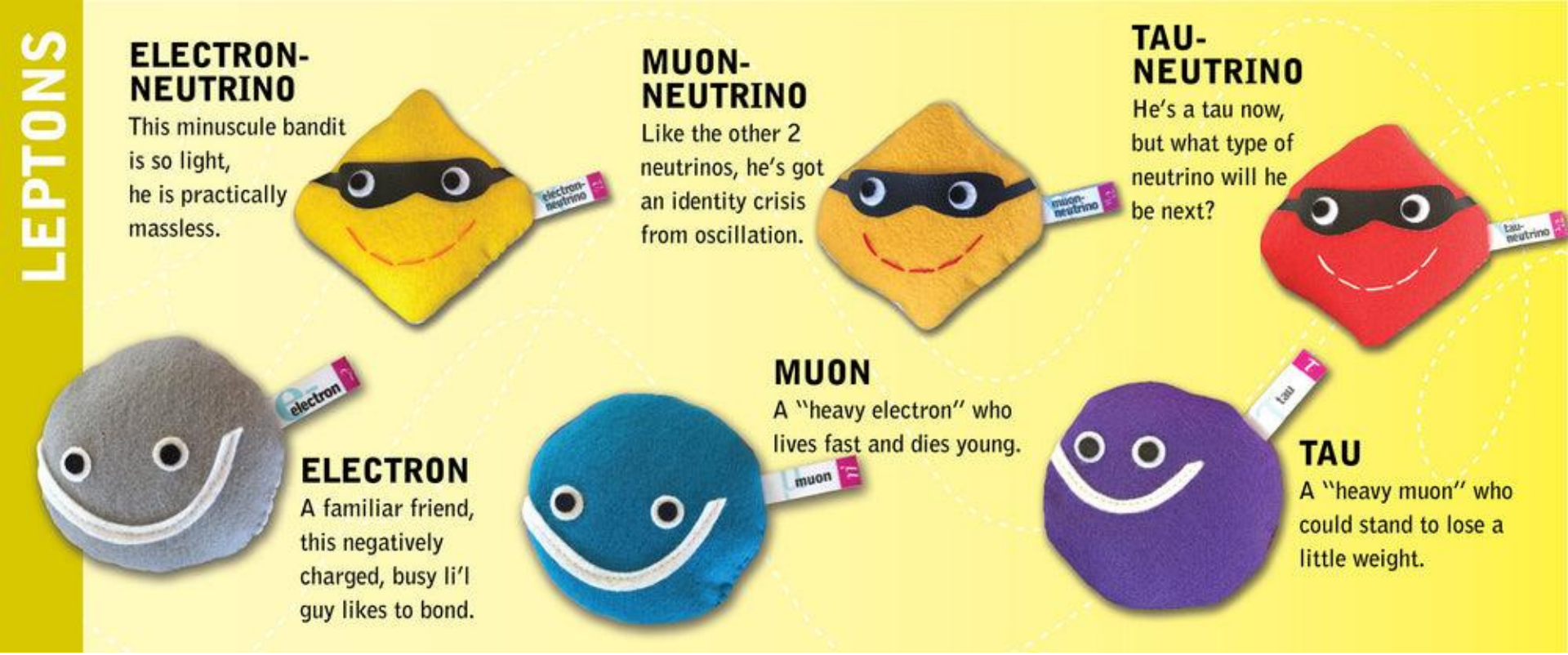




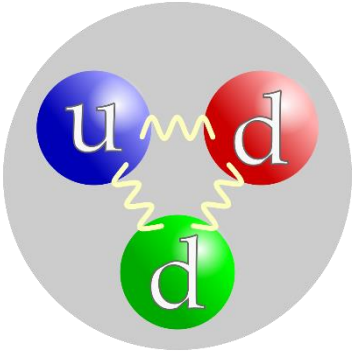
The Standard Model plan



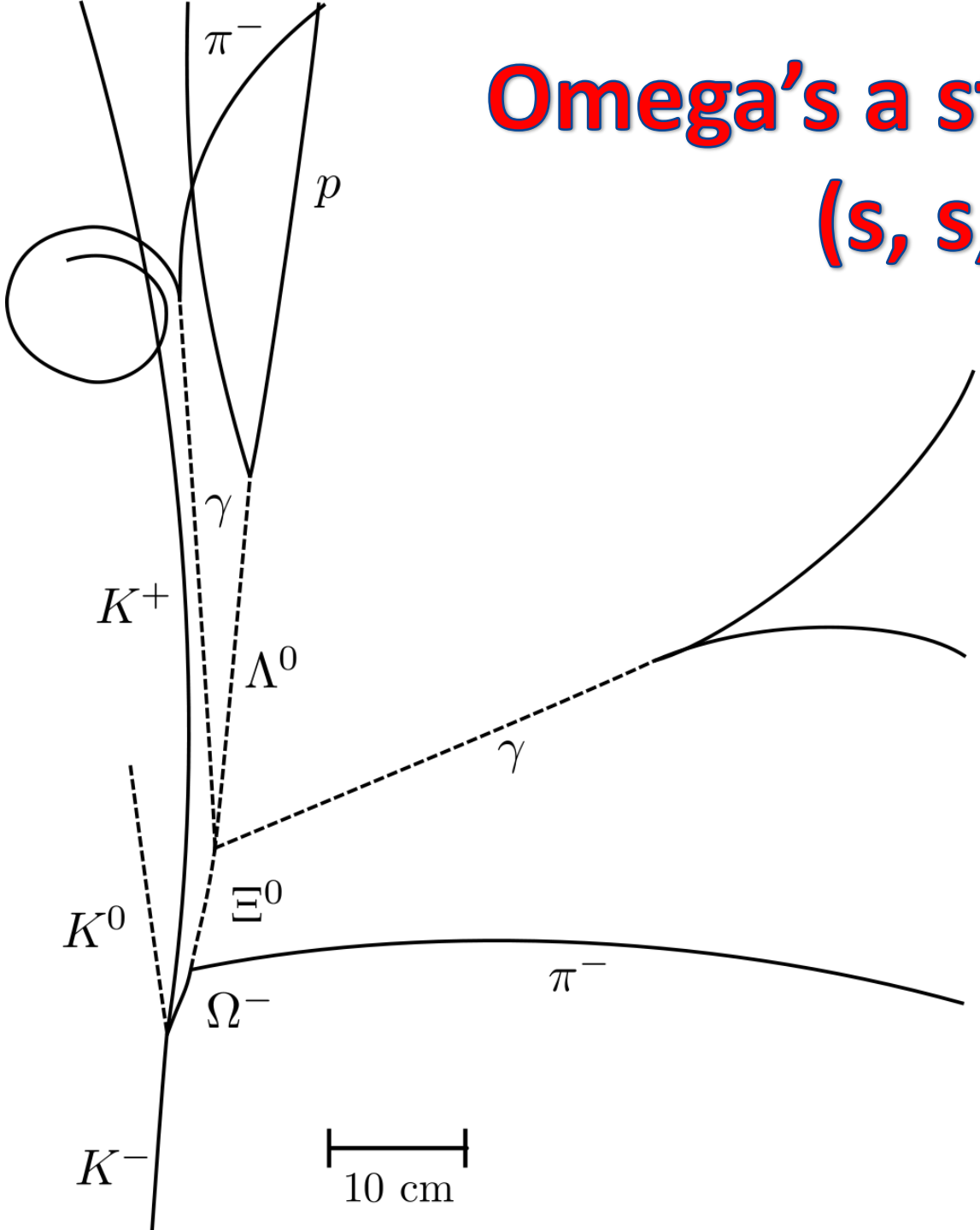
Of an accelerator near you…

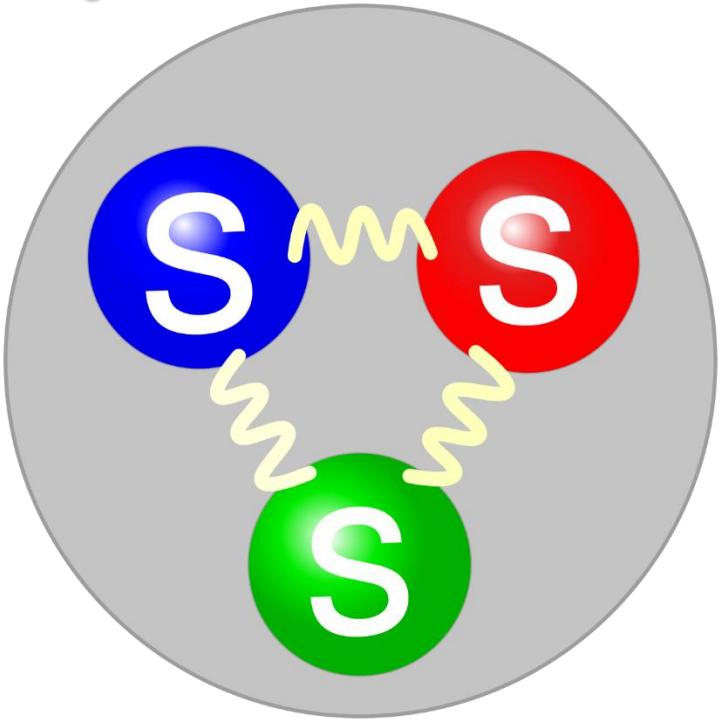


Leptons aren't hadrons like neutrons (up, down, down)



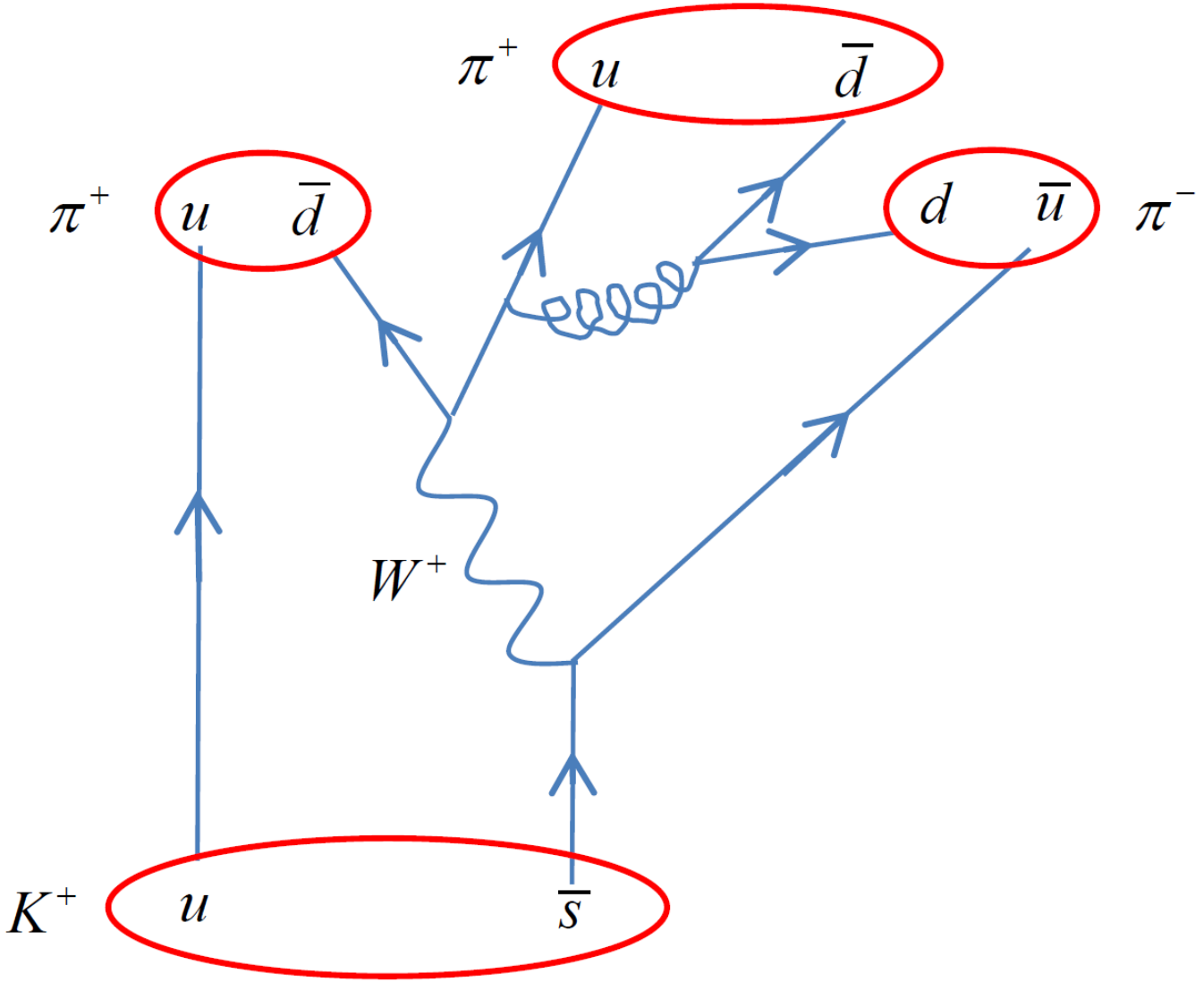
Omega's a strange one (s, s, s)





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

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



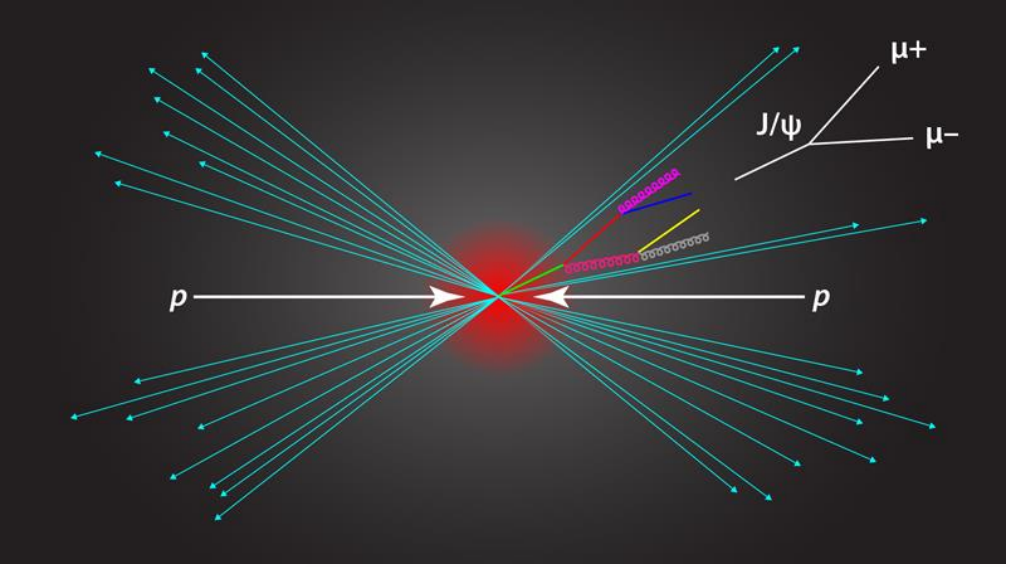
There's kaons and pions (u s bar, u d bar)

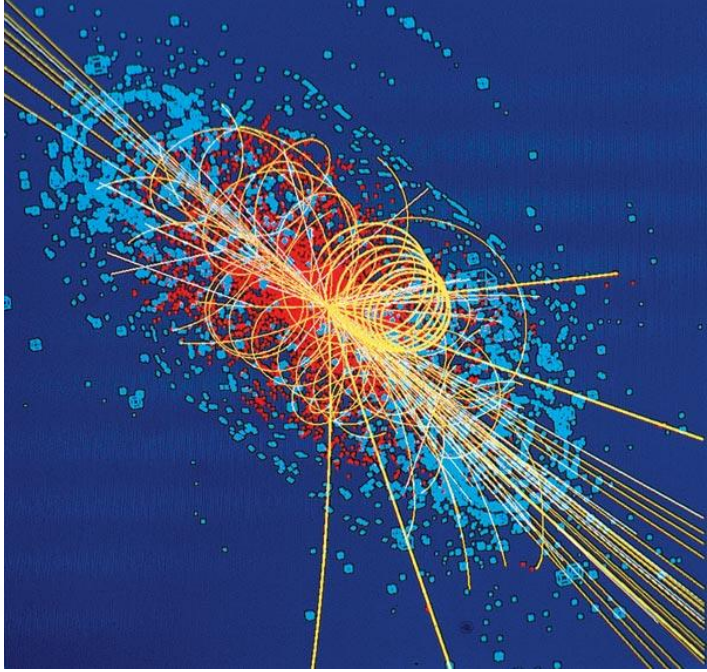
mass	≈2.2 MeV/c²	≈1.28 GeV/c²	≈173.1 GeV/c²
charge	⅔	⅔	⅔
spin	½	½	½
QUARKS	u up	c charm	t top
	≈4.7 MeV/c²	≈96 MeV/c²	≈4.18 GeV/c²
	−⅓	−⅓	−⅓
	½	½	½
	d down	s strange	b bottom

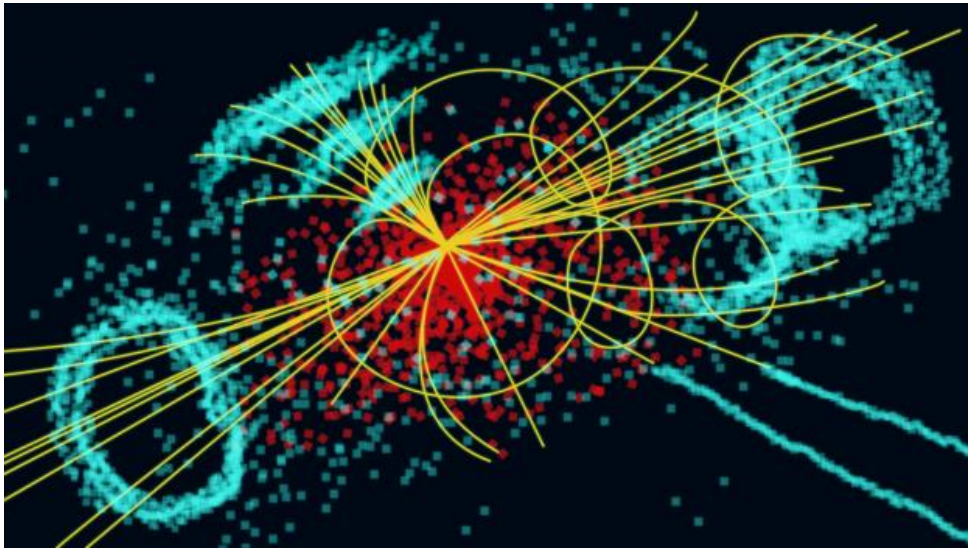
0	
0	g gluon
1	

But the quarks

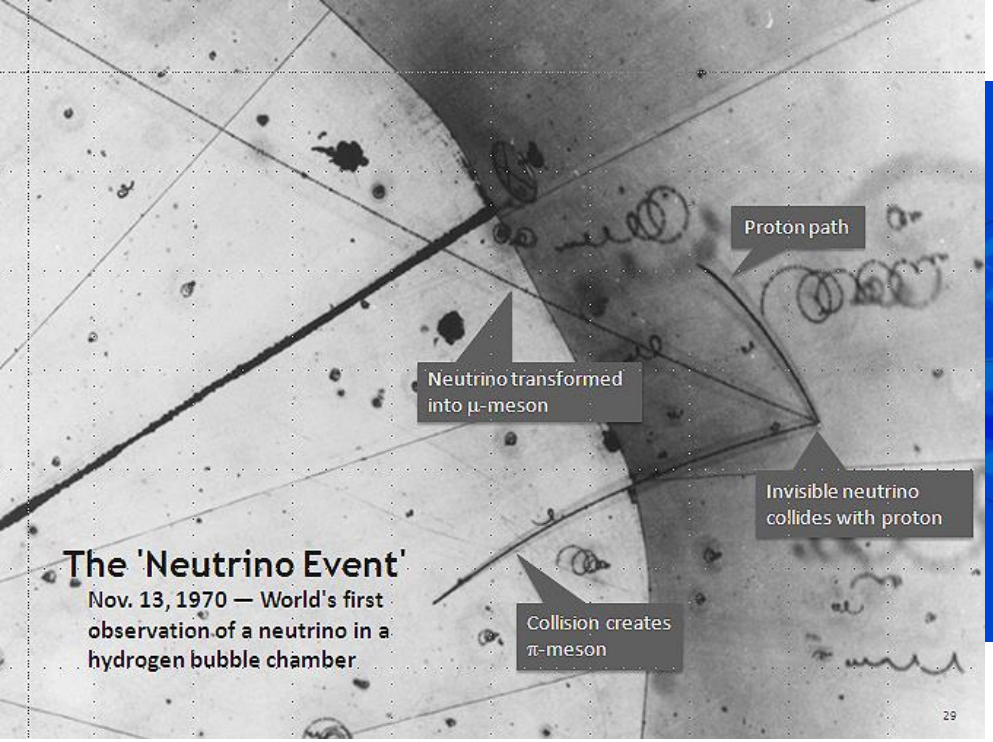
with their gluons ain't free….!

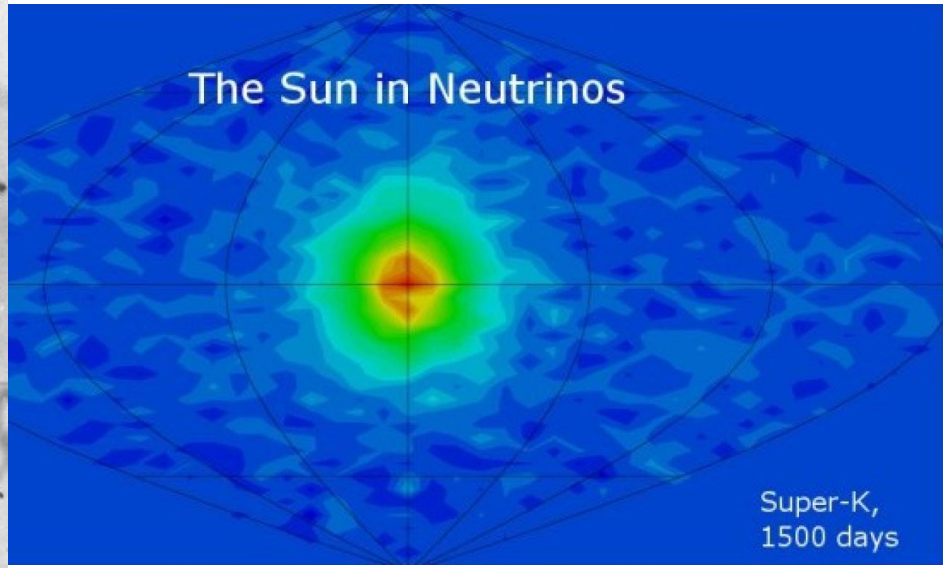


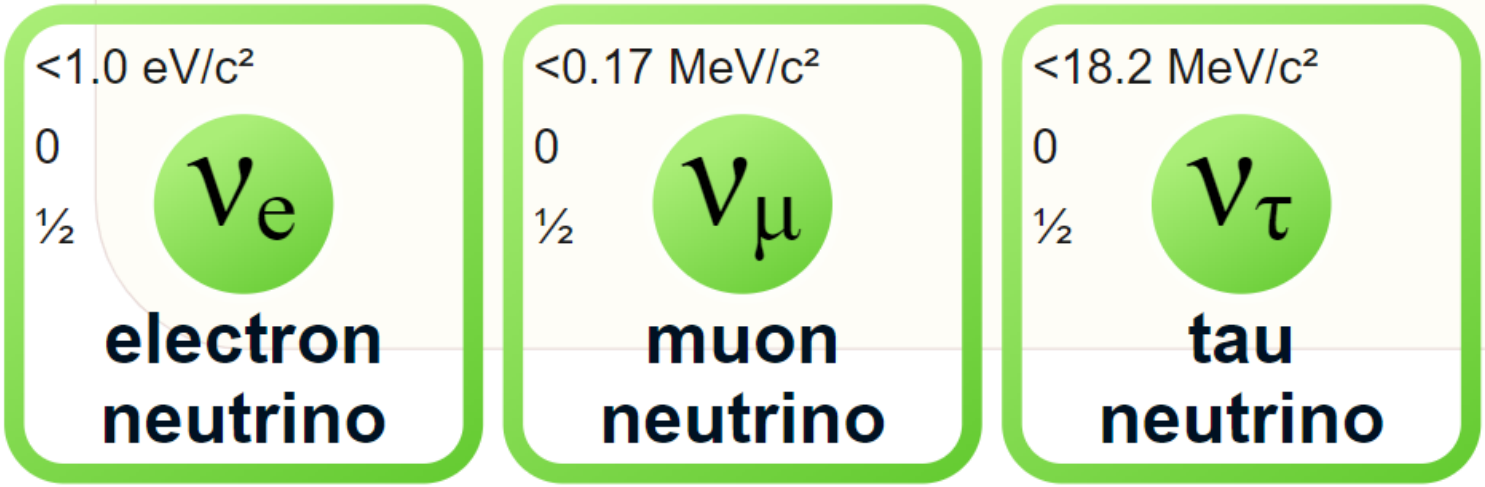




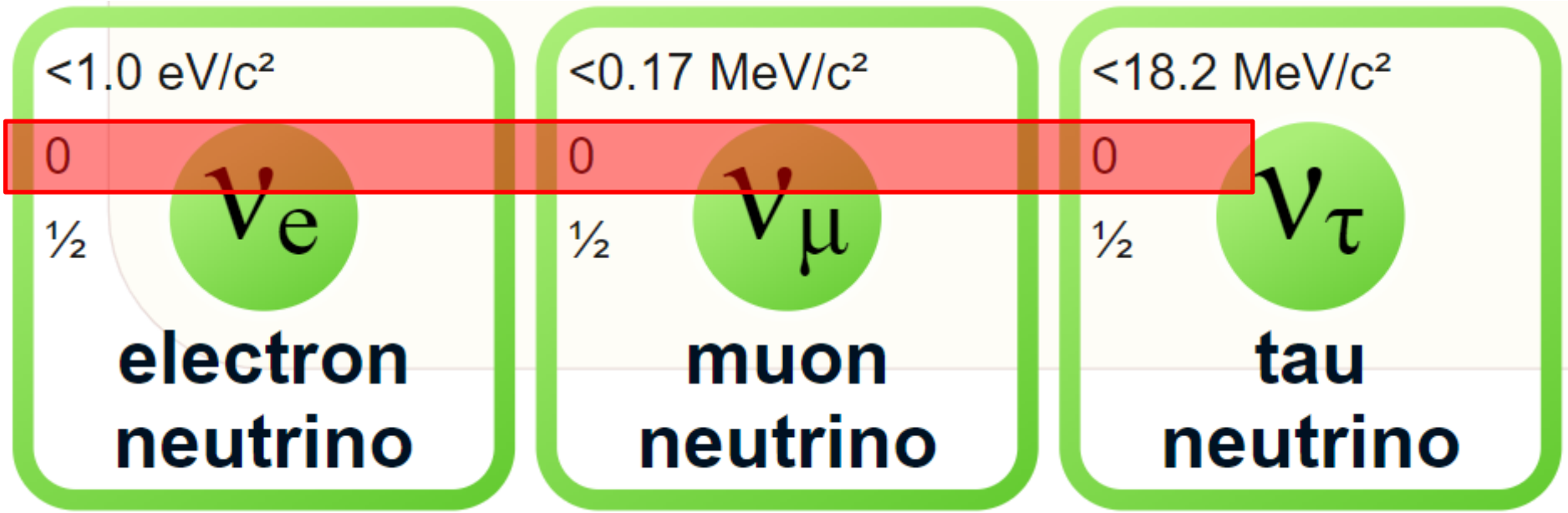
* Amazing guitar solo! *







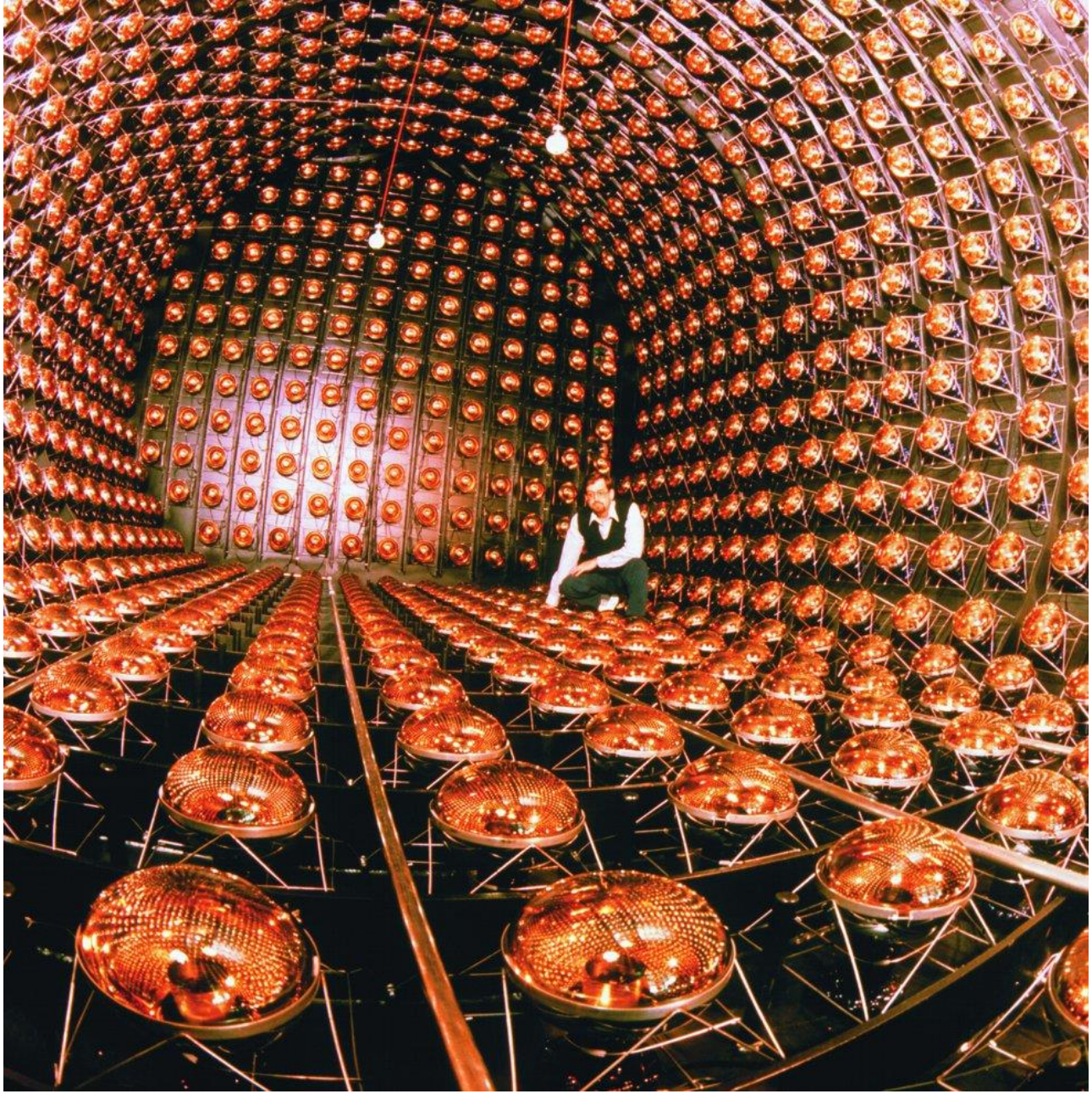
I've told you about neutrinos



They don't have a charge

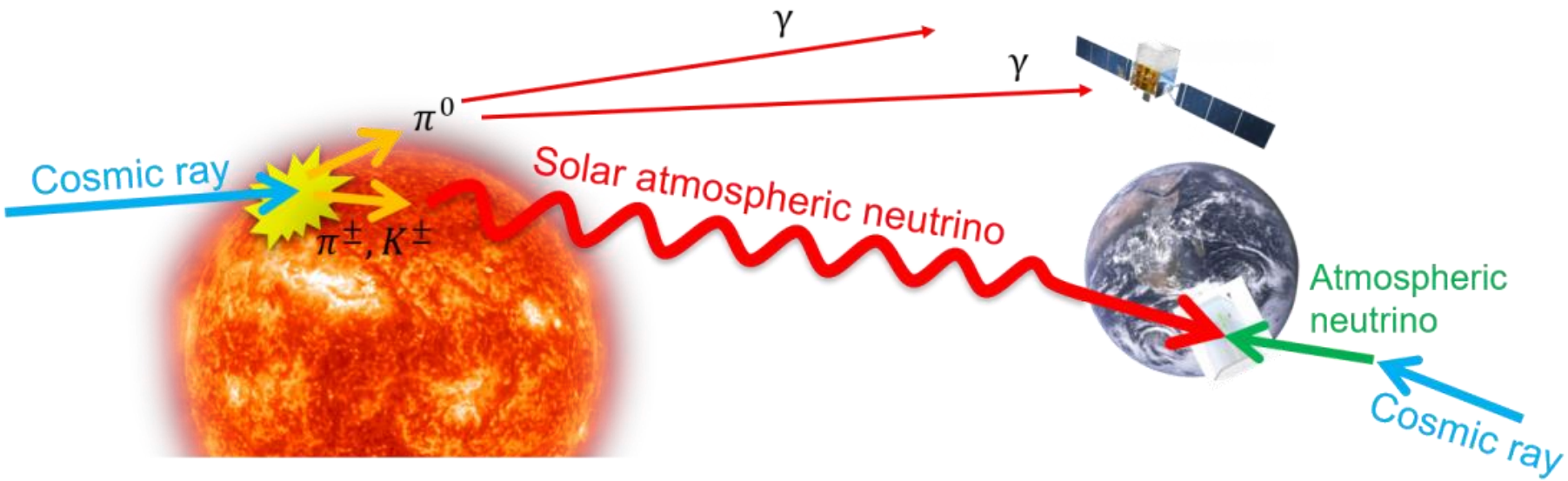
$$m_\nu < 2.14 \times 10^{-37}\,\mathrm{kg}$$

But might have a bit of mass



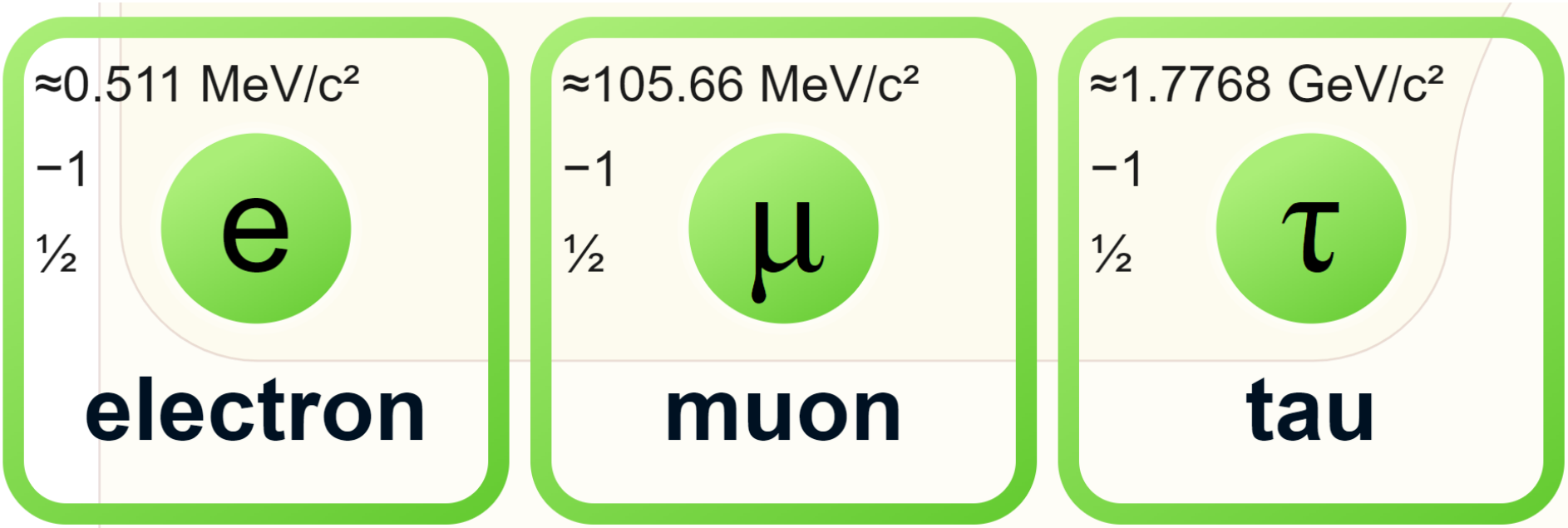
To detect them is a pain in the ass!

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

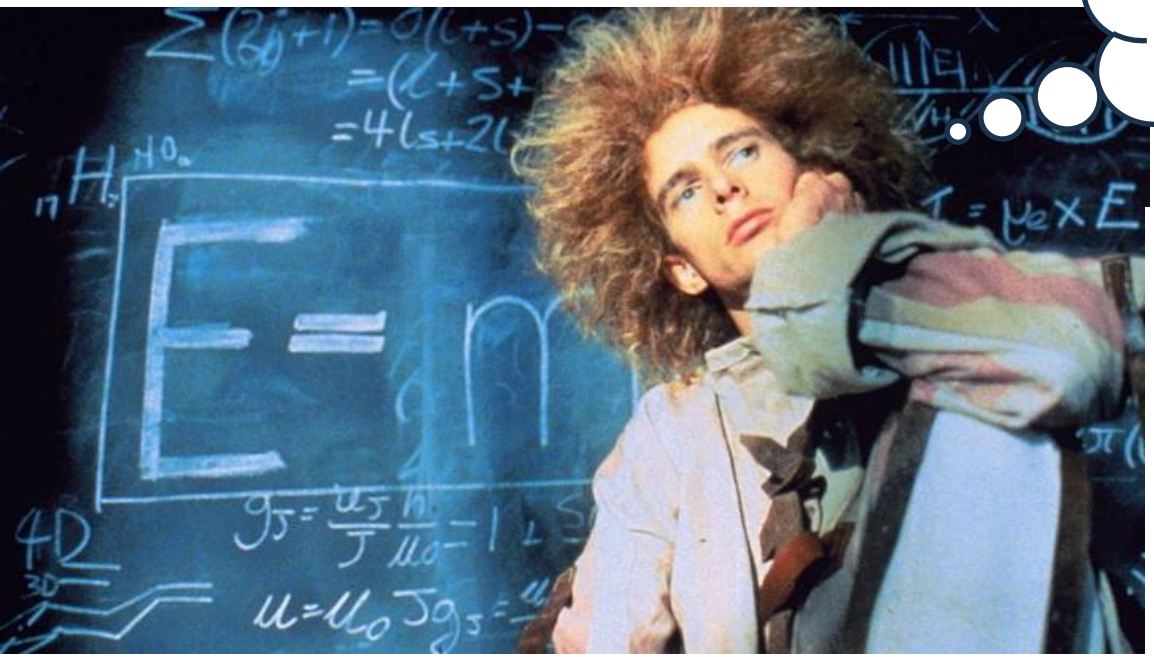


Trillions of them

are now passing through you


≈0.511 MeV/c²
−1
½
e
electron
≈105.66 MeV/c²
−1
½
μ
muon
≈1.7768 GeV/c²
−1
½
τ
tau

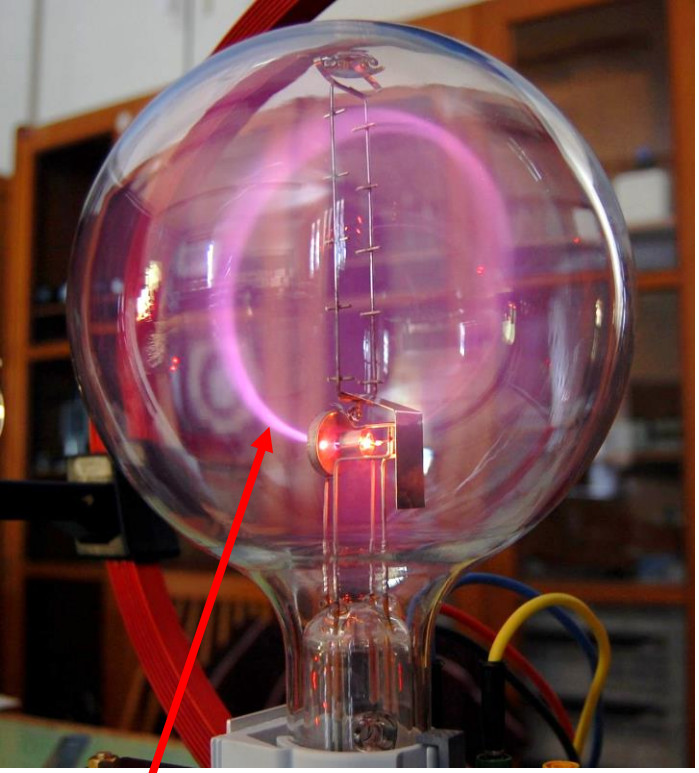
e, mu and tau



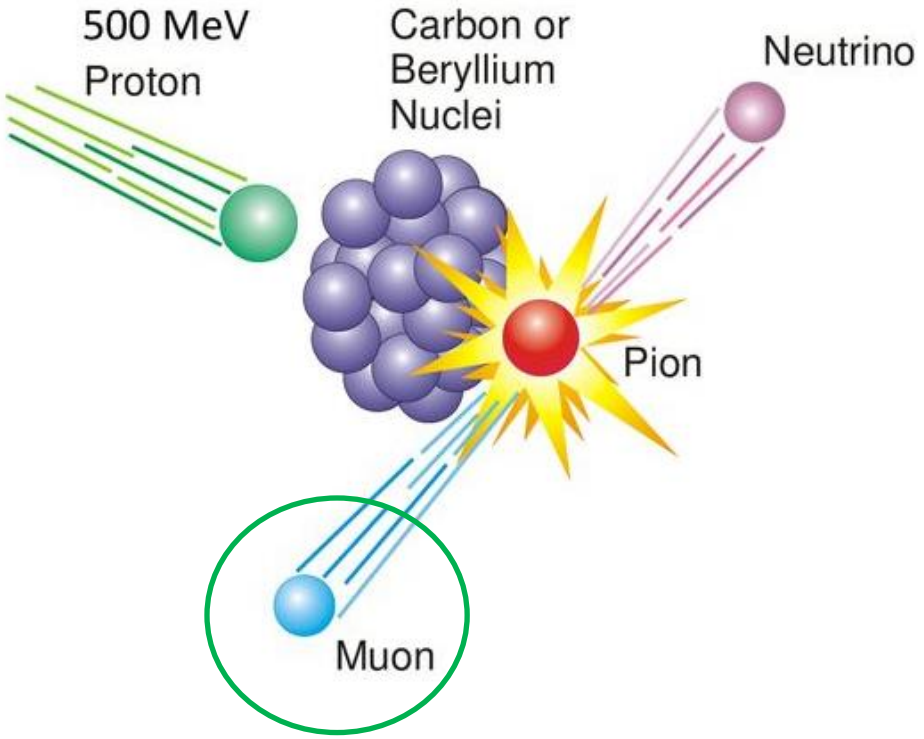
You can try, but it won't work!

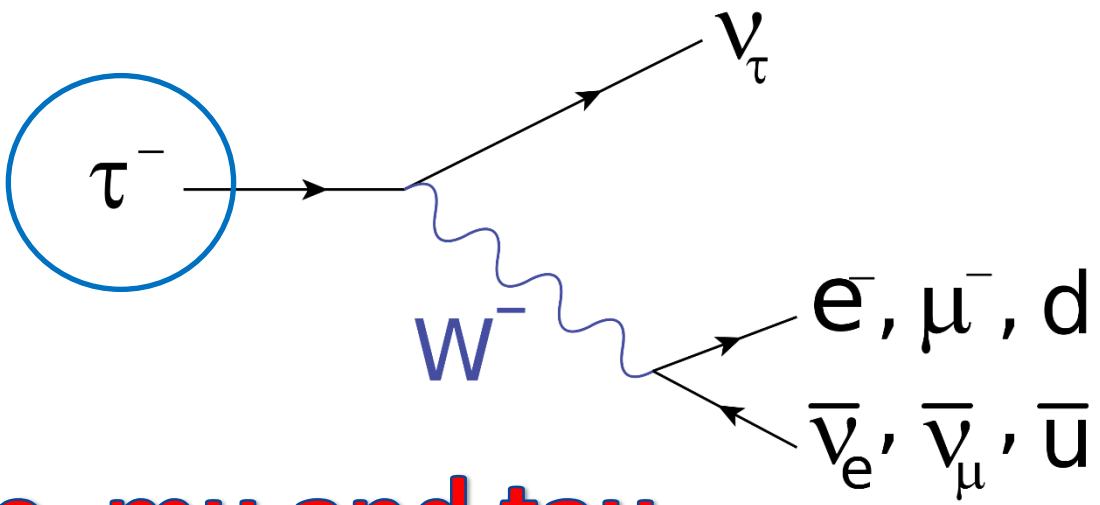
They're fundamental

can't split an electron

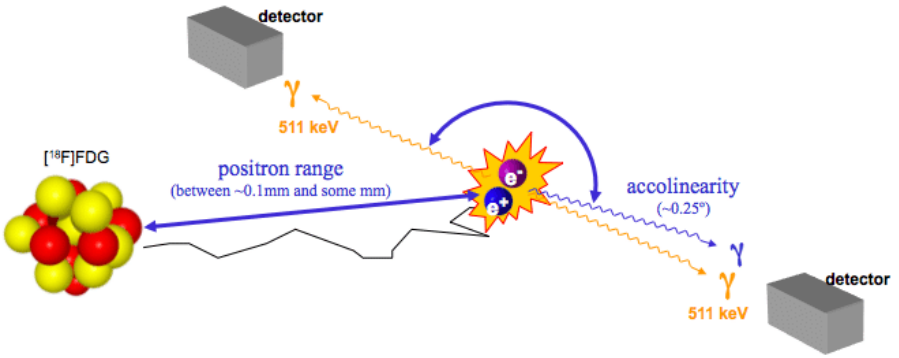


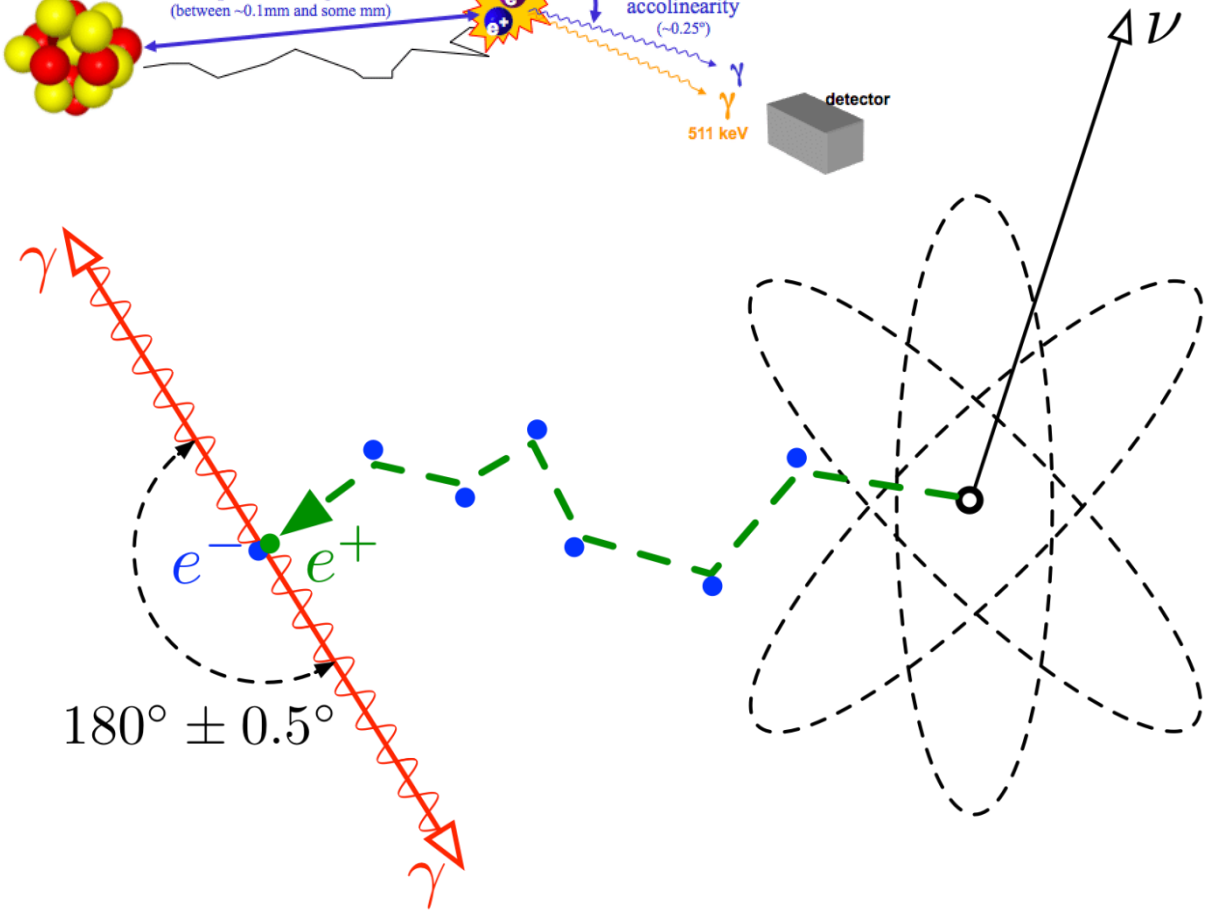
e^-


500 MeV
Proton
Carbon or
Beryllium
Nuclei
Neutrino
Pion
Muon


ν_τ
τ^-
W^-
e^-, μ^-, d
$\bar{\nu}_e, \bar{\nu}_\mu, \bar{u}$

e, mu and tau





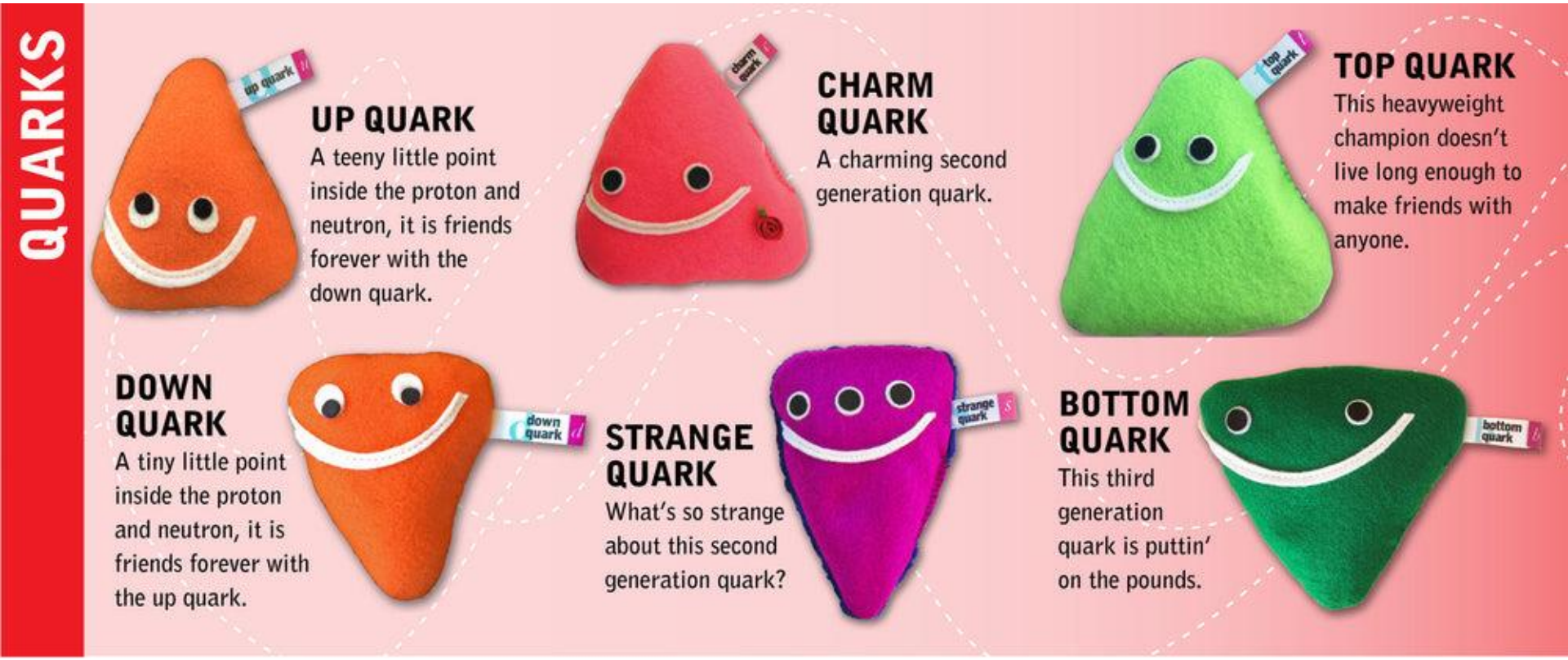
e^+ positron

e^- electron

ν neutrino

γ quantum/photon (511 keV)

Add a positron and make two photons!



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

https://www.particlezoo.net/collections/quarks

≈2.2 MeV/c²

⅔

½

u

up

≈4.7 MeV/c²

−⅓

½

d

down

≈1.28 GeV/c²

⅔

½

c

charm

There's up, down and charm

≈96 MeV/c²

−⅓

½

s

strange

≈4.18 GeV/c²

−⅓

½

b

bottom

≈173.1 GeV/c²

⅔

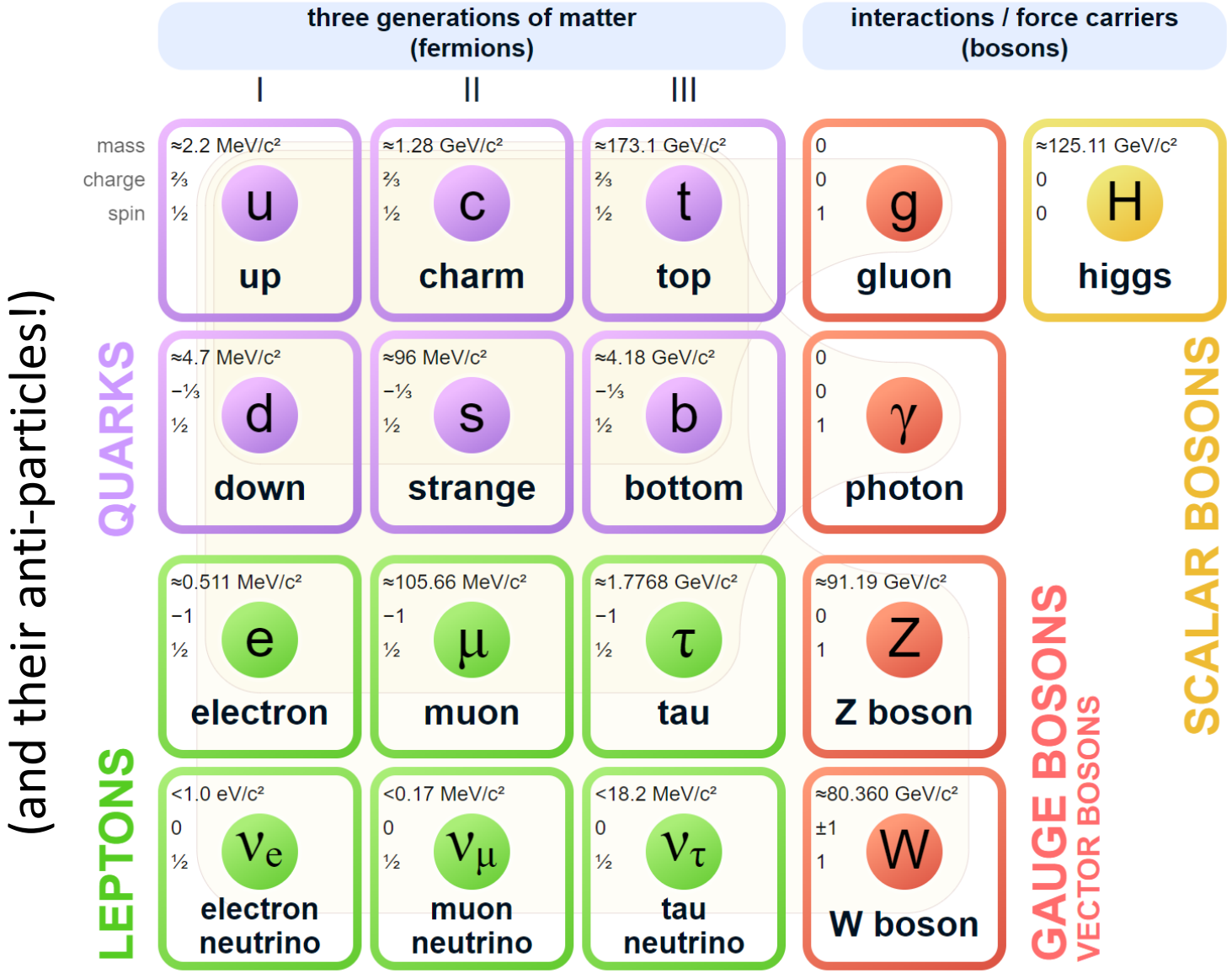
½

t

top

And strange, bottom and top…

Standard Model of Elementary Particles



(and their anti-particles!)

Dada! (etc…)