PHYS252 Quantum Physics and Applications

Module 5: Particle Physics_3

Dr. Shikha Bangar

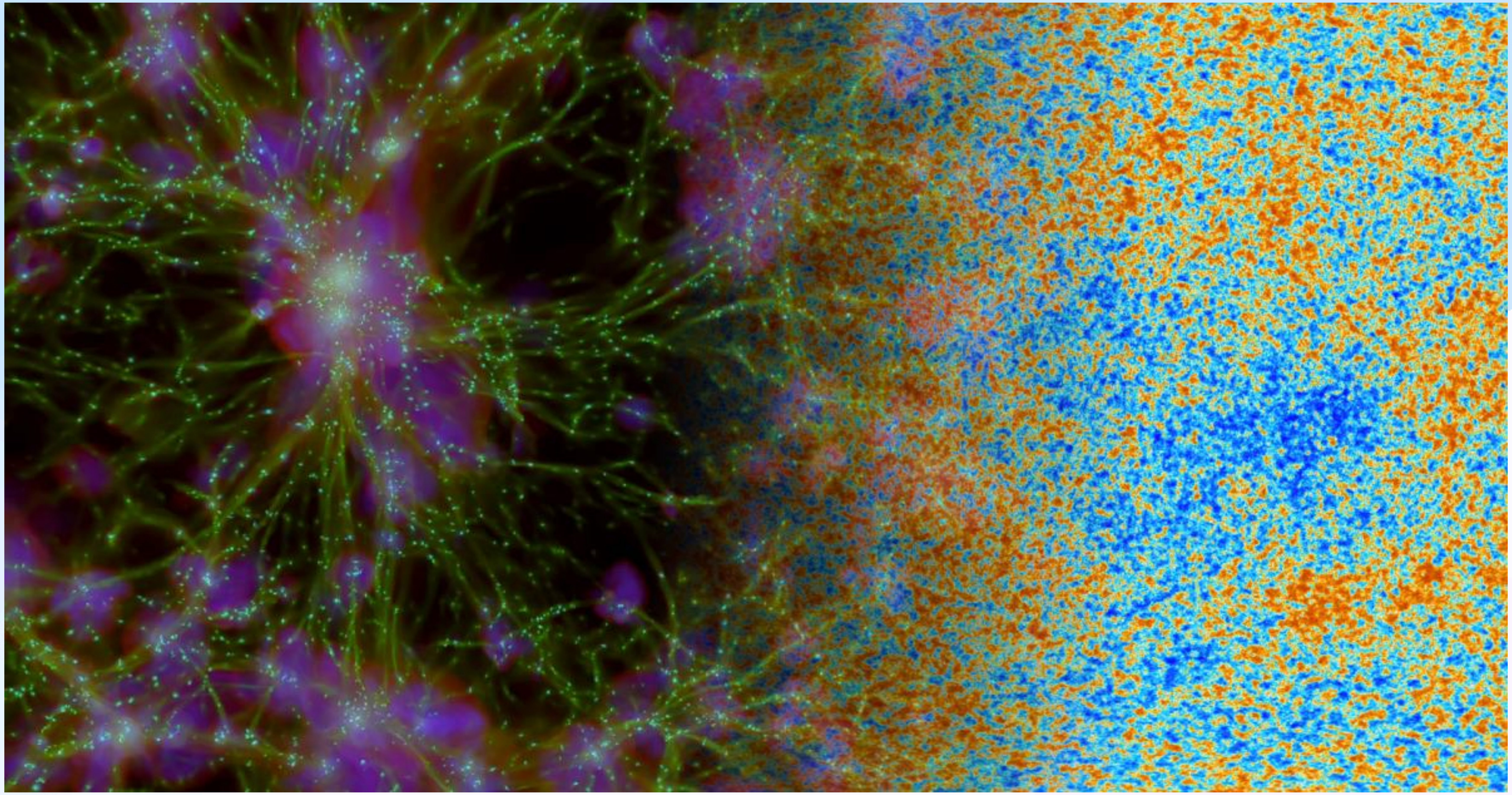
Announcements

- Here is the plan for rest of the semester:

Week	Monday	Wednesday	Friday	Labs	Deadlines
4. 21	Elementary Phy	Cosmology	Cosmology	10. CERN HEP	HW 7 due on April 21
4. 28	Quantum Applications	Special Relativity and more	Review - 1	Make-up labs (email by April 25)	HW 8 due on May 1
5. 5	Review - 2	No class	-	-	
May 13th Final Exam from 1:00 - 3:00 PM, BUE-415					

Module 5

- Particle Physics
- Cosmology



Problem 1

The Ω^- baryon has S = -3. (a) It is desired to produce the Ω^- using a beam of K^- incident on protons. What other particles are produced in this reaction?
(b) How might the Ω^- decay?

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TABLE 14.5 Some Selected Mesons

Particle	Antiparticle	Charge* (e)	Spin ($\hbar$)	Strangeness*	Rest Energy (MeV)
π^+	π^-	+1	0	0	140
π^0	π^0	0	0	0	135
K^+	K^-	+1	0	+1	494
K^0	$\overline{K}^0$	0	0	+1	498
η	η	0	0	0	548
ρ^+	ρ^-	+1	1	0	775
η'	η'	0	0	0	958
D^+	D^-	+1	0	0	1869
J/ψ	J/ψ	0	1	0	3097
B^+	B^-	+1	0	0	5279
Υ	Υ	0	1	0	9460

Problem 1

The Ω^- baryon has S = -3. (b) How might the Ω^- decay?

TABLE 14.6 Some Selected Baryons

Particle	Antiparticle	Charge* (e)	Spin ($\hbar$)	Strangeness*
p	$\bar{p}$	+1	$\frac{1}{2}$	0
n	$\bar{n}$	0	$\frac{1}{2}$	0
Λ^0	$\overline{\Lambda}^0$	0	$\frac{1}{2}$	−1
Σ^+	$\overline{\Sigma}^+$	+1	$\frac{1}{2}$	−1
Σ^0	$\overline{\Sigma}^0$	0	$\frac{1}{2}$	−1
Σ^-	$\overline{\Sigma}^-$	−1	$\frac{1}{2}$	−1
Ξ^0	$\overline{\Xi}^0$	0	$\frac{1}{2}$	−2
Ξ^-	$\overline{\Xi}^-$	−1	$\frac{1}{2}$	−2
Δ^*	$\overline{\Delta}^*$	+2, +1, 0, −1	$\frac{3}{2}$	0
Σ^*	$\overline{\Sigma}^*$	+1, 0, −1	$\frac{3}{2}$	−1
Ξ^*	$\overline{\Xi}^*$	−1, 0	$\frac{3}{2}$	−2
Ω^-	$\overline{\Omega}^-$	−1	$\frac{3}{2}$	−3

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Particle Interactions and Decay (Chapter-14.4)

- How do we do these experiments?

- The elementary particles, most of which are unstable and do not exist in nature, must be created in violent collisions.

- For this purpose we need a high-energy beam of particles and a suitable target of elementary particles.

- The only strongly interacting, stable elementary particle is the **proton**, and thus a hydrogen target is a logical choice. To get a reasonable density of target atoms, researchers often use liquid, rather than gaseous, hydrogen

Particle Interactions and Decay

- For a suitable beam, we must be able to accelerate a particle to very high energies

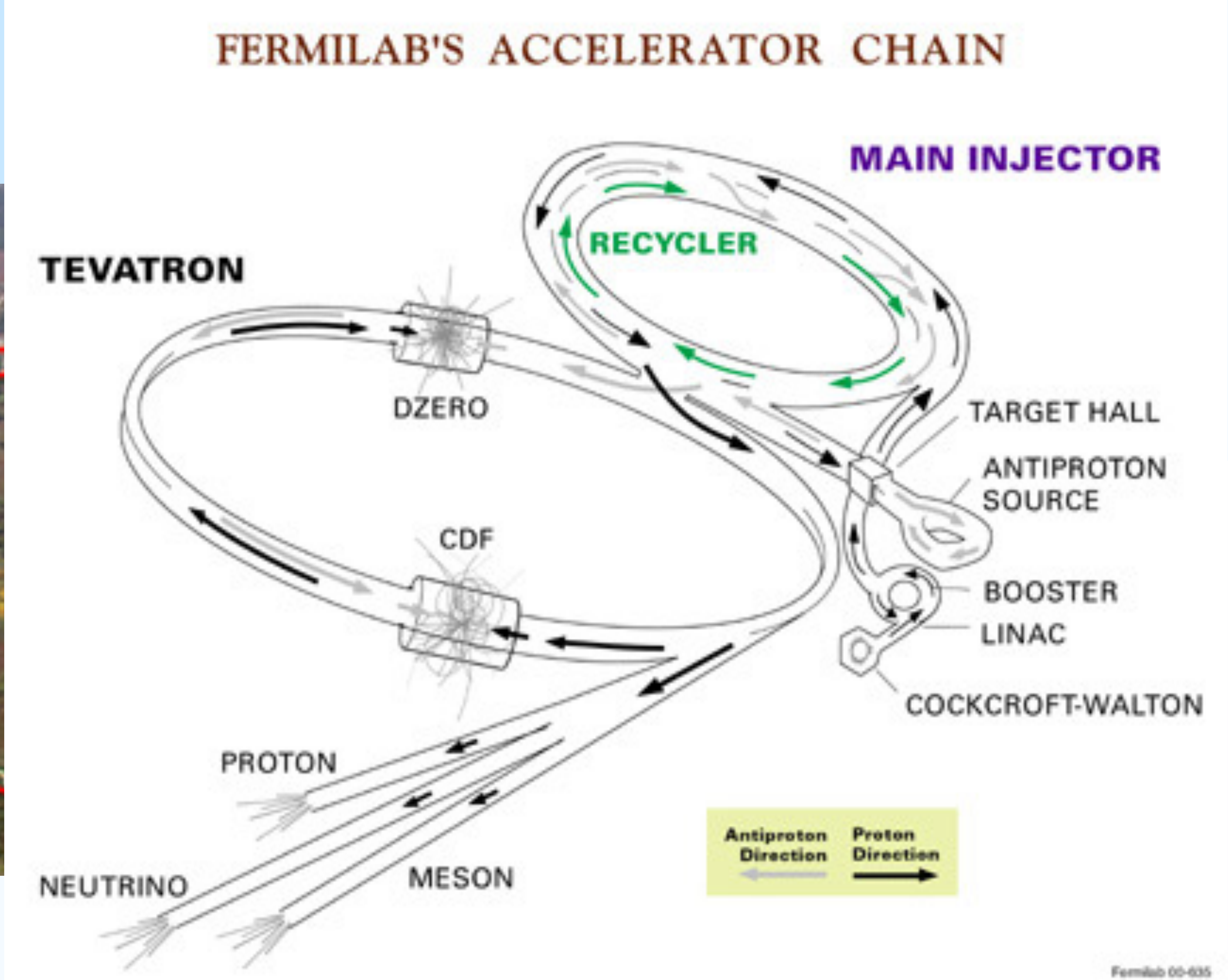
- A stable charged particle is the logical choice for the beam; stability is required because of the relatively long time necessary to accelerate the particle to high energies, and a charged particle is required so that electromagnetic fields may be used to accelerate the particle.

- Once again the proton is a convenient choice, and thus many particle physics reactions are produced using beams of high-energy protons

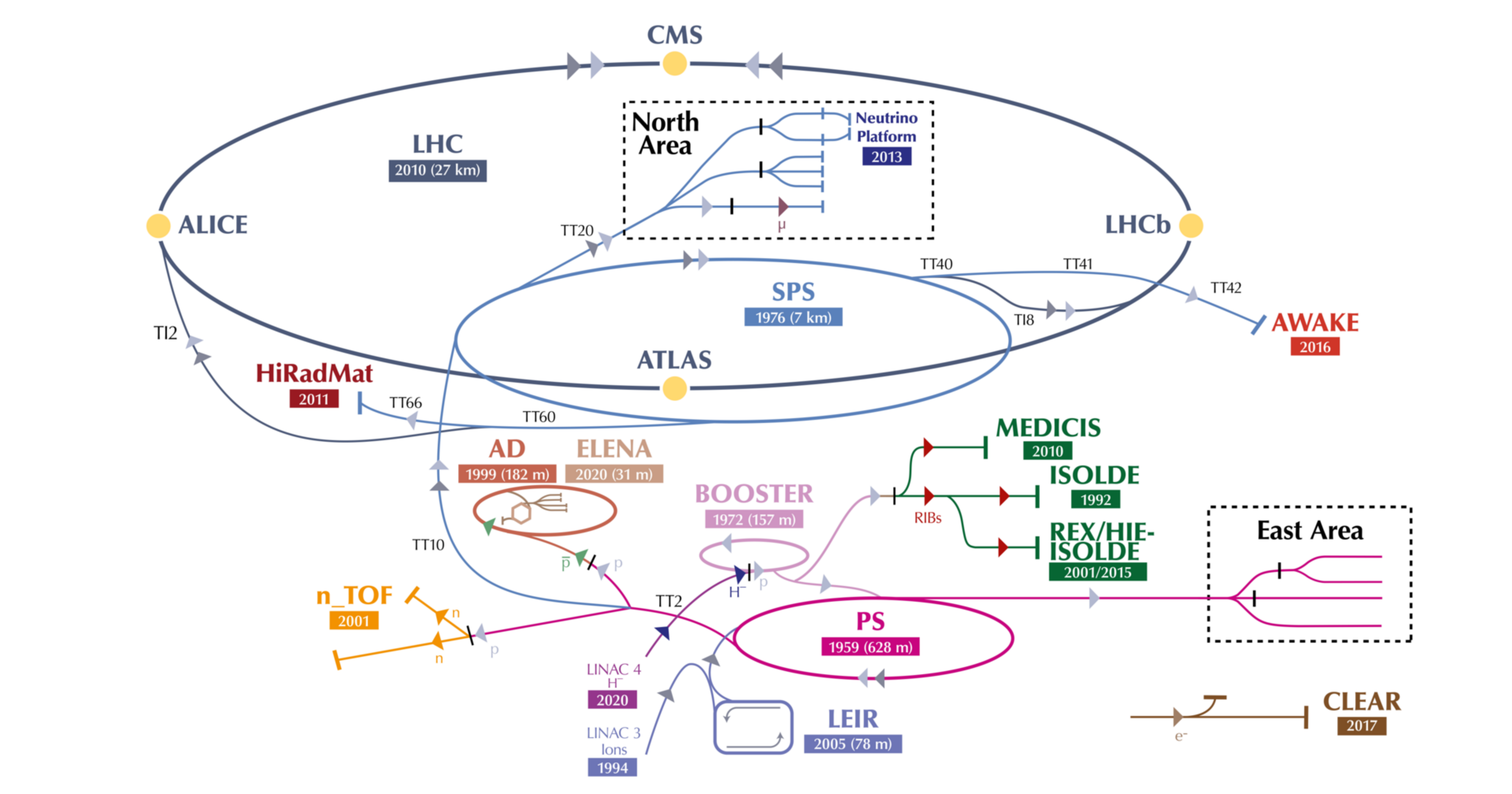
$$\mathrm{p} + \mathrm{p} \rightarrow \text{product particles}$$

Fermi Lab

Fermi Lab

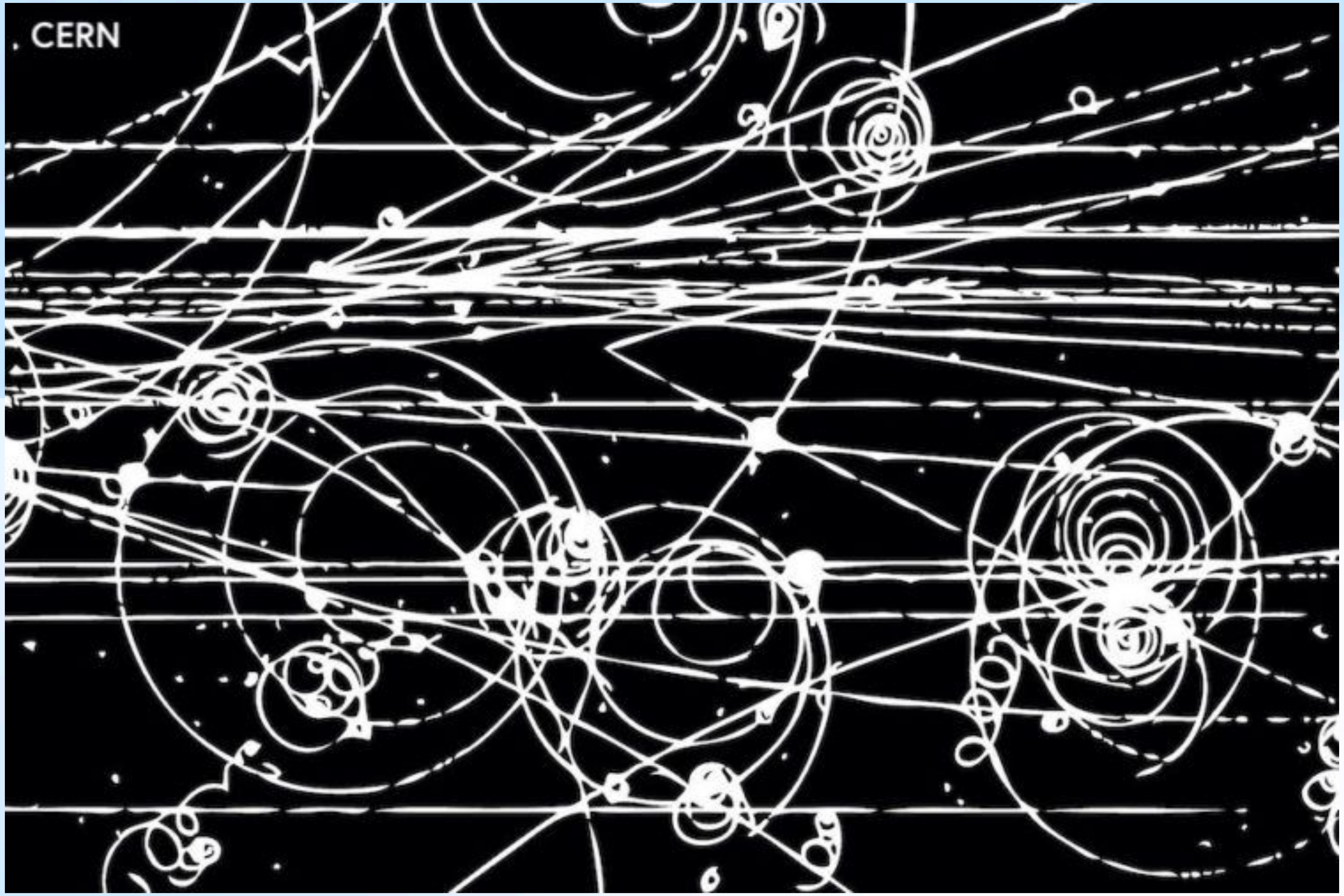

FERMILAB'S ACCELERATOR CHAIN
MAIN INJECTOR
RECYCLER
TEVATRON
DZERO
TARGET HALL
ANTIPROTON SOURCE
CDF
BOOSTER
LINAC
COCKCROFT-WALTON
PROTON
NEUTRINO
MESON
Antiproton Direction
Proton Direction

CERN



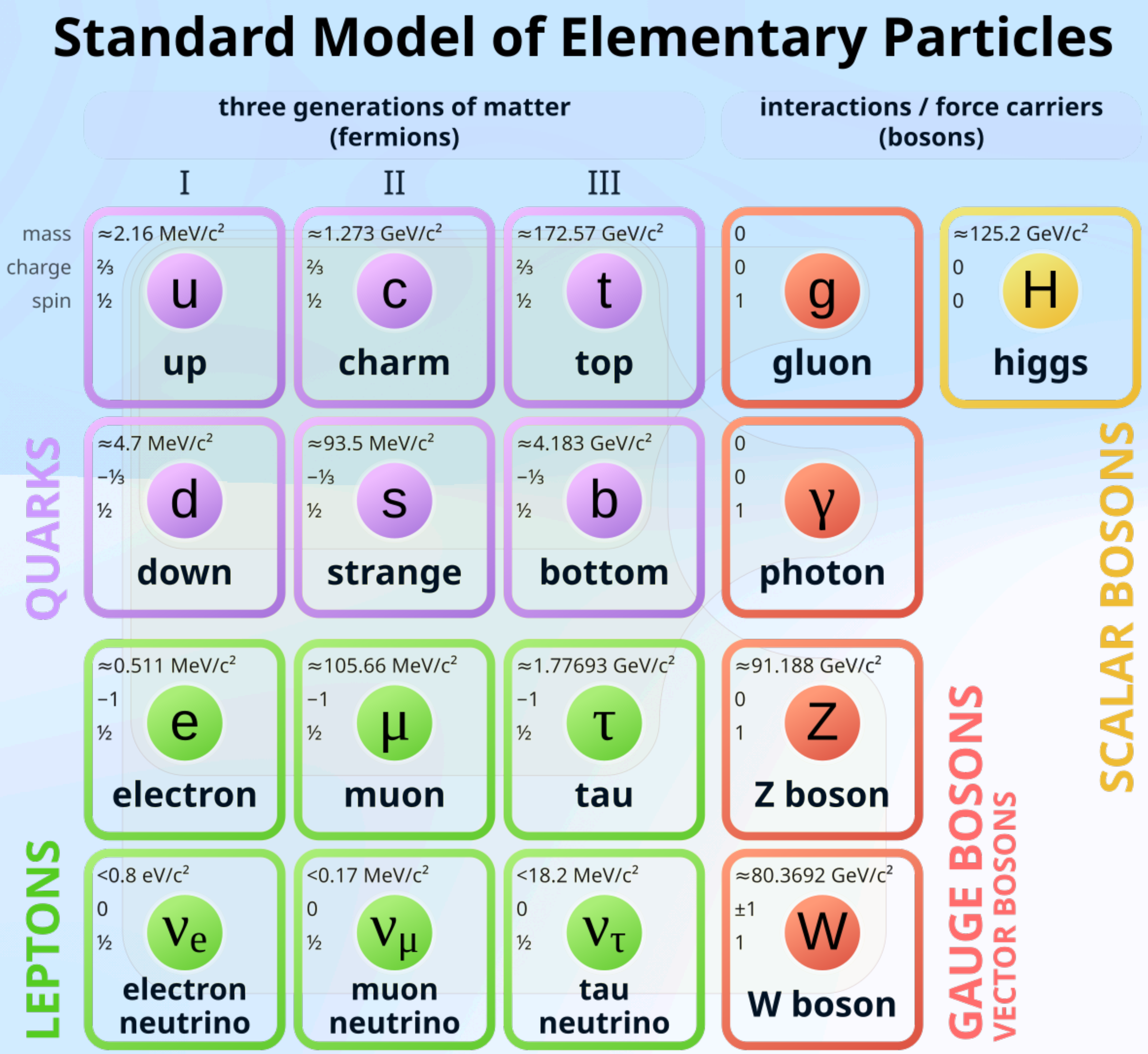
CMS
LHC
2010 (27 km)
North Area
Neutrino Platform
2013
ALICE
LHCb
TT20
μ
TT40
TT41
TT42
SPS
1976 (7 km)
TI8
AWAKE
2016
TI2
ATLAS
HiRadMat
2011
TT66
TT60
MEDICIS
2010
AD
1999 (182 m)
ELENA
2020 (31 m)
ISOLDE
1992
BOOSTER
1972 (157 m)
RIBs
REX/HIE-ISOLDE
2001/2015
East Area
TT10
p̄
p
H⁻
n_TOF
2001
n
TT2
PS
1959 (628 m)
LINAC 4
H⁻
2020
LINAC 3
Ions
1994
LEIR
2005 (78 m)
CLEAR
2017
e⁻

Detecting Particles



- The particles produce visible tracks in the detector so that their identity and direction of travel can be determined
- A magnetic field must be present, so that the resulting curved trajectory of a charged particle can be used to determine its momentum and the sign of its charge.

Energy and Momentum in Particle Decay (14.5)



All 2nd and 3rd generation quickly decay into the 1st generation particles

Energy and Momentum in Particle Decay (14.5)

The decays of elementary particles follow these two rules:

1. Like nuclear decays: $Q = (m_i - m_f)c^2$ where $m_i c^2$ is the rest energy of the initial particle, and $m_f c^2$ is the total rest energy of all the final products. The decays only occur when Q is positive.

2. The available energy Q is shared as kinetic energy of the decay products in such a way as to conserve linear momentum. Back-to-back decays where there are two products, with unique energy. For decays with three or more products, each particle has a distribution of energies from zero to a maximum, like beta decay.

Problem 2

Compute the energies of the proton and π meson that result from the decay of a Λ^0 at rest.

Problem 3

Compute the Q values for the reactions:

(a) $\pi^- + p \rightarrow K^0 + \Lambda^0$

(b) $K^- + p \rightarrow \Lambda^0 + \pi^0$

What are quarks?

- Ordinary matter (protons and neutrons) are made of (mostly) only two types of quarks “Up” (u) and down (d)

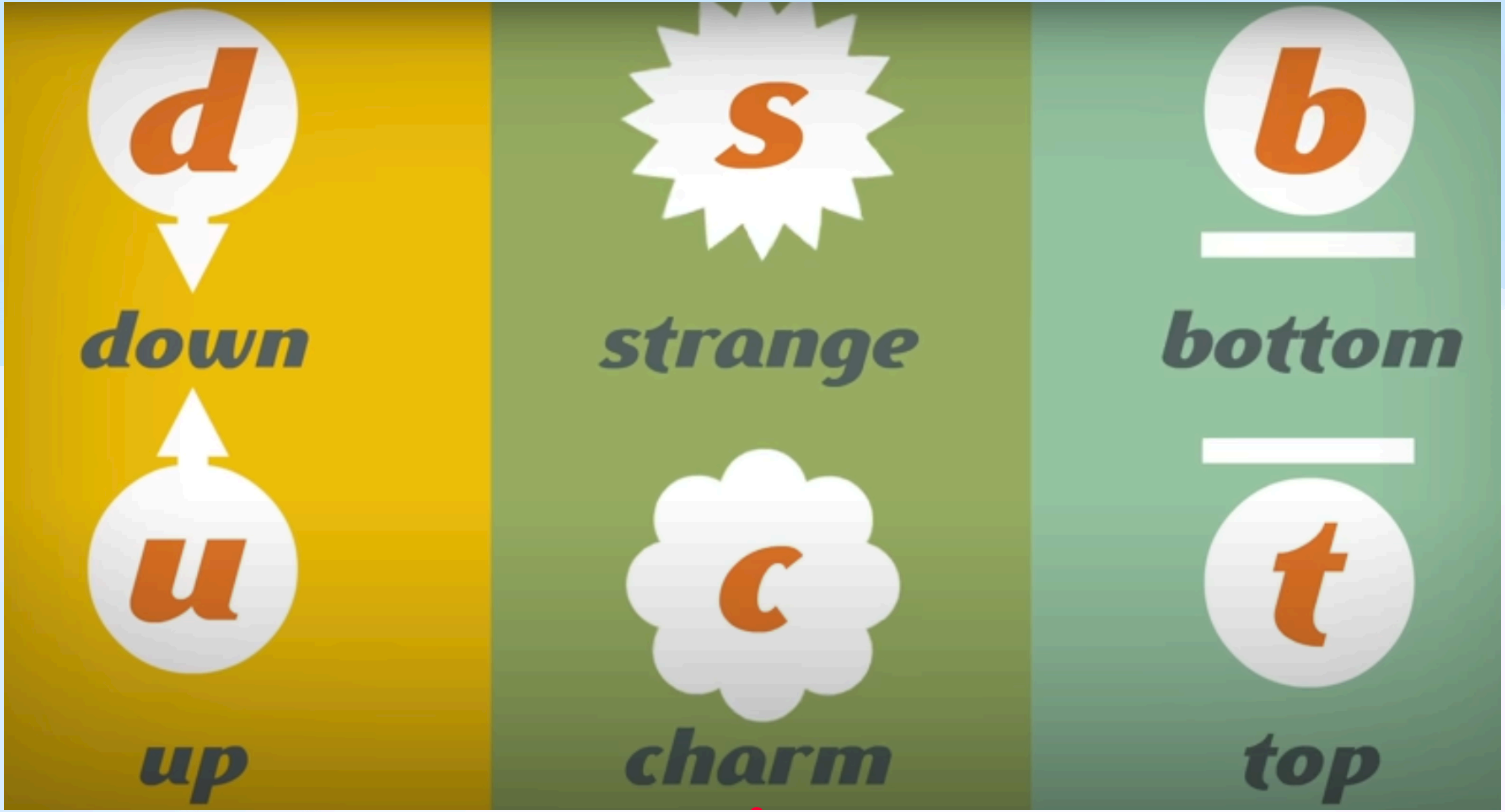
- Proton =uud, Neutron- udd

- Quarks carry a baryon number of 1/3 (or quark number 1) and are spin-1/2 particles

- The first generation is stable, and the higher generation is unstable particles

Q=(+2/3)e	up	charm	top
Q=(-1/3)e	down	strange	bottom
Generations:	I	II	III

Quarks



What are quarks?

- Note: Anti-quarks: Have the same mass as quarks, s= ½, but opposite quantum numbers (electric charge, strangeness/charmness/topness/bottomness)

Q=(+2/3)e	up, (330MeV)	charm (1.5GeV) C=+1	top (172GeV) T=+1
Q=(-1/3)e	down, (330MeV)	strange (500MeV) S=-1	bottom (4.7GeV) B=-1

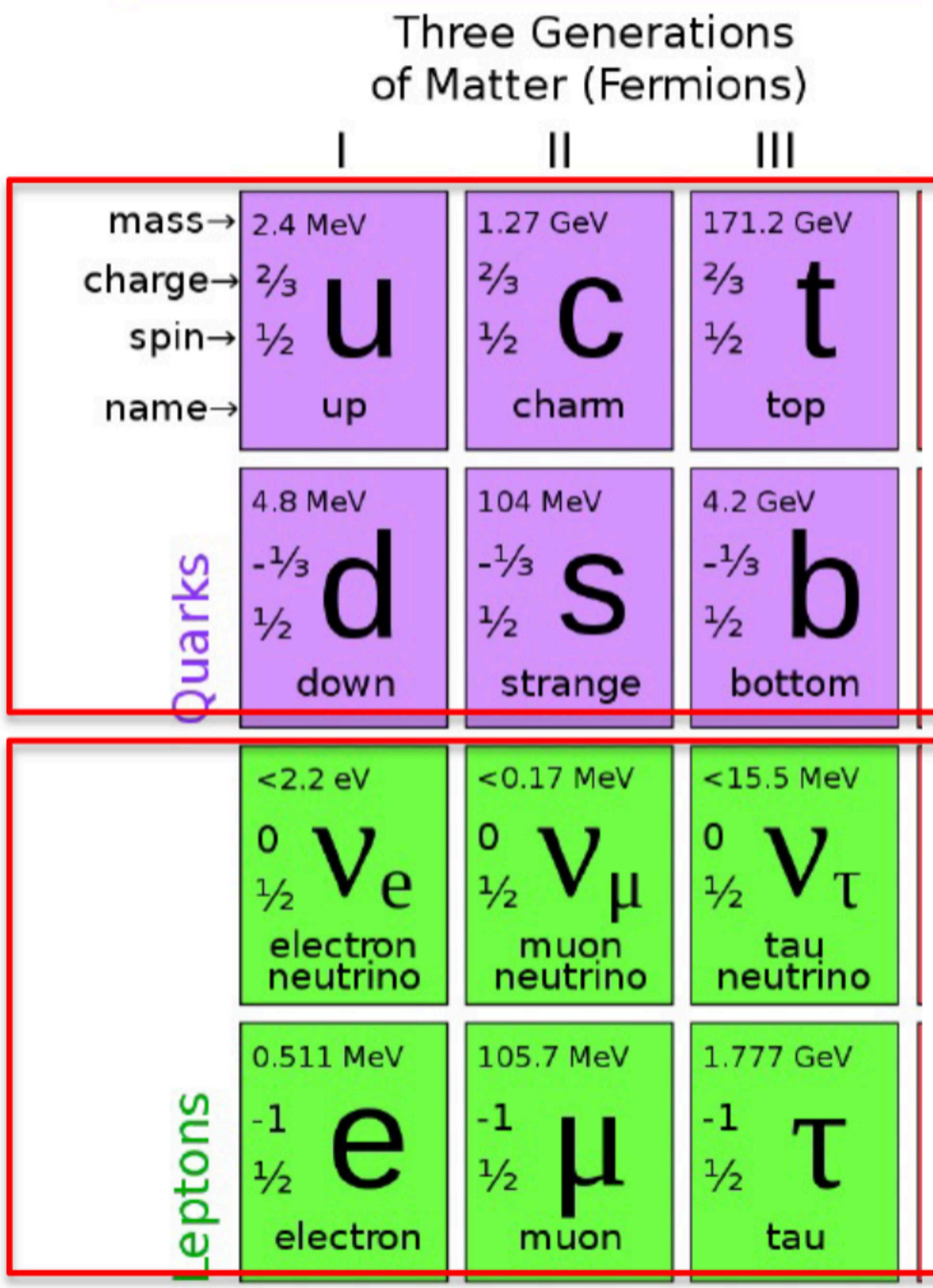
Generations: I (stable) II (not stable) III (not stable)

lower mass → higher mass

Quarks

Name	Symbol	Particle Charge (e)	Spin $(\hbar)$	Baryon #	Rest Energy (MeV)	Properties
Up	u	$+\frac{2}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	330	C=S=T=B=0
Down	d	$-\frac{1}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	330	C=S=T=B=0
Charm	c	$+\frac{2}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	1500	C=1
Strange	s	$-\frac{1}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	500	S=-1
Top	t	$+\frac{2}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	172,000	T=1
Bottom	b	$-\frac{1}{3}$	$\frac{1}{2}$	$+\frac{1}{3}$	4700	B=-1

Quarks

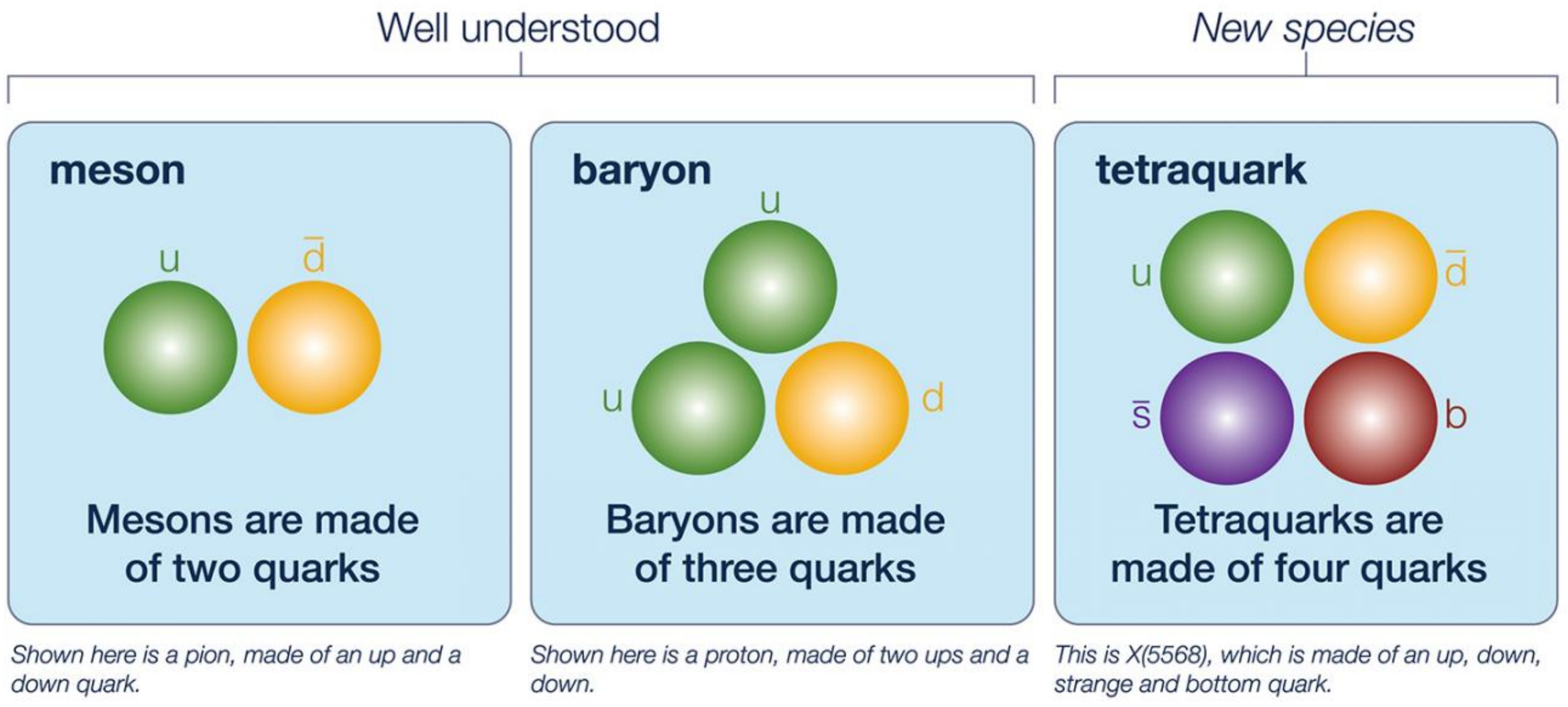


Quarks form mesons and baryons

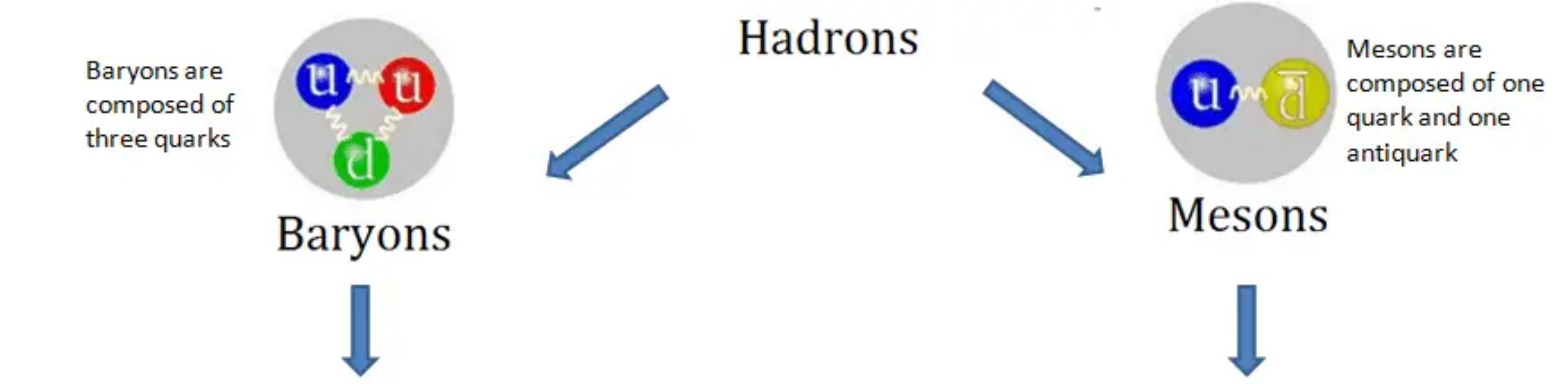
Which are collectively called **hadrons**

6 leptons: 3 generations

The Quark Structure of Mesons and Baryons



The Quark Structure of Mesons and Baryons



Nucleons

Particle	Mass (MeV/c^2)	τ (sec)
p	938.2	$>10^{11}$
n	939.5	10^3

Hyperons

Particle	Mass (MeV/c^2)	τ (sec)
Λ	1115	2.6×10^{-10}
Σ^+	1189	0.8×10^{-10}
Σ^0	1192	10^{-14}
Σ^-	1197	1.6×10^{-10}
Ξ^0	1314	3×10^{-10}
Ξ^-	1321	1.8×10^{-10}
Ω^-	1675	1.3×10^{-10}

Pions

Particle	Mass (MeV/c^2)	τ (sec)
π^-, π^+	139	2.5×10^{-8}
π^0	135	1.8×10^{-16}

Kaons

Particle	Mass (MeV/c^2)	τ (sec)
K^-, K^+	494	1.2×10^{-8}
K^0	498	
η	550	10^{-18}

- Just looking at meson and baryon table, it is a lot
- We can illustrate this order if we plot a diagram that has strangeness along the y axis and electric charge along the x axis.
- If the families of particles are placed in their proper locations on the graphs, regular geometrical patterns begin to emerge.

Mesons

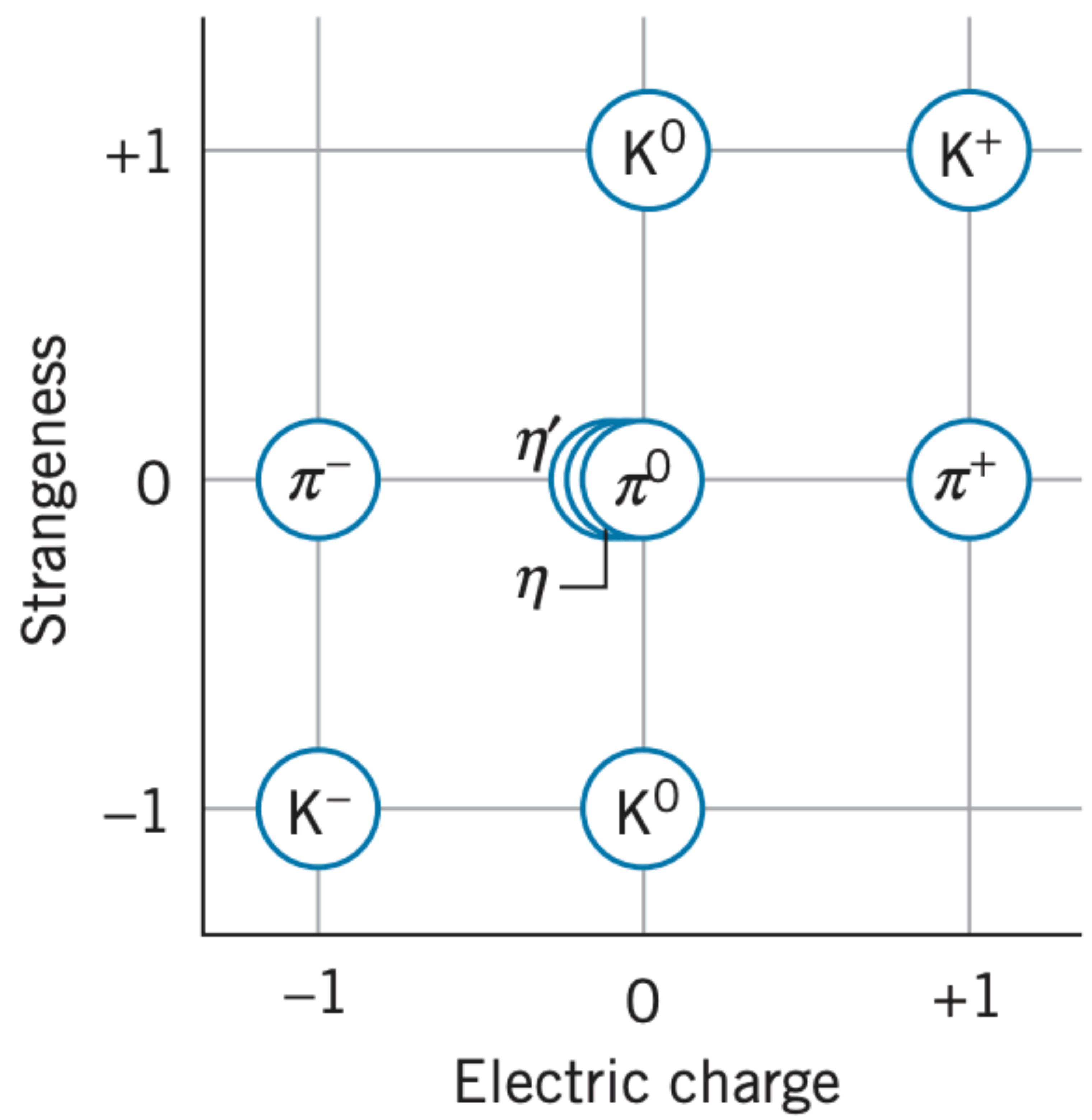
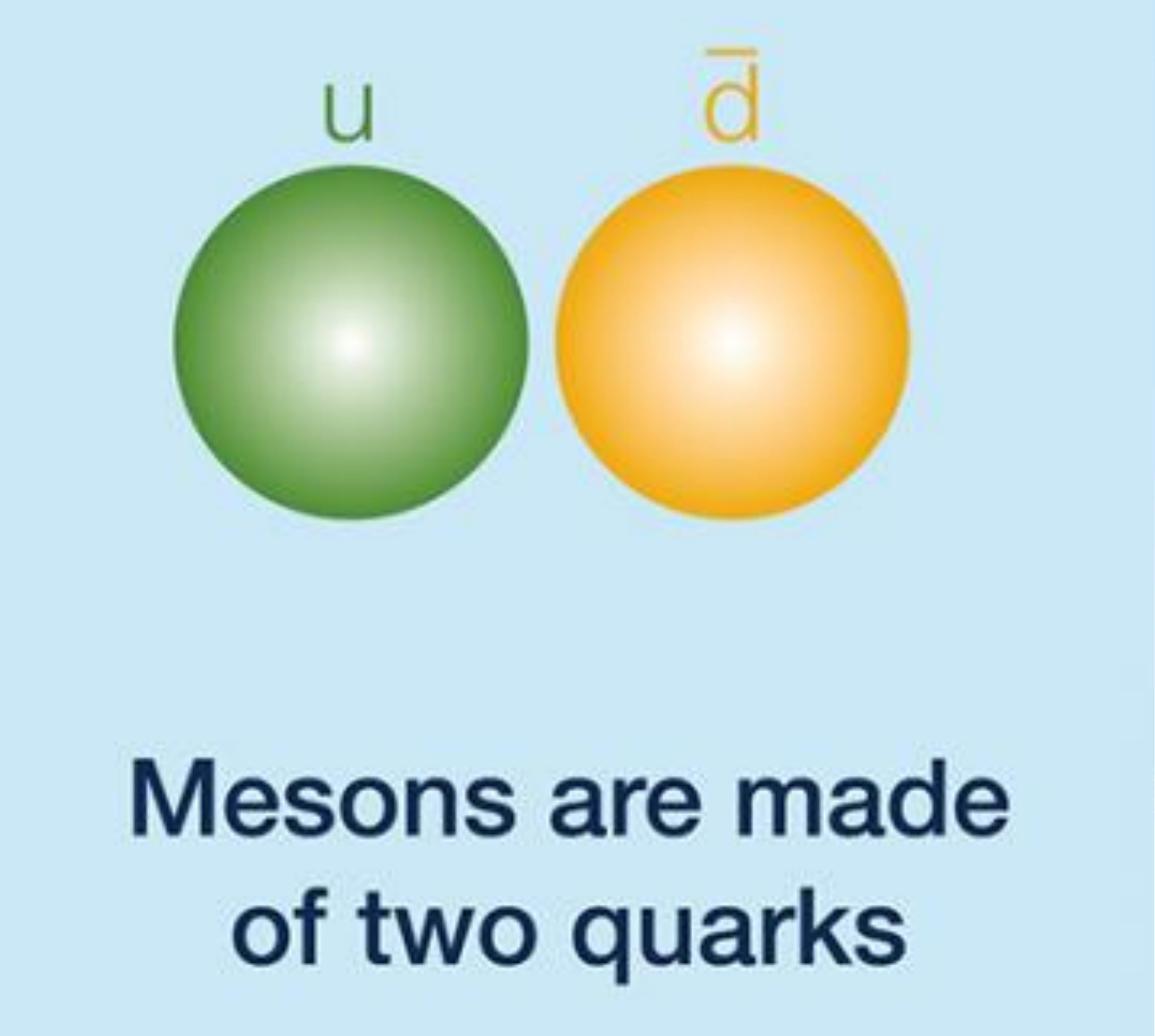


FIGURE 14.11 The relationship between electric charge and strangeness for the spin-0 mesons.

- Let us see how the quark model works in the case of the spin-0 mesons.
- The quarks have spin 1/2 , so the simplest scheme to form a spin-0 meson would be to combine two quarks, with their spins directed oppositely.
- However, the mesons have baryon number B = 0, while combining two quarks would have B = 1/3 + 1/3 = 2/3.
- A combination of a quark and an antiquark has B = 0 (as antiquark will have B = -1/3)

Mesons



- For example, suppose we combine a u quark with a $\bar{d}$ ("antidown") quark, obtaining the combination $u\bar{d}$.

- This combination has:
  - spin zero and
  - electric charge 2/3 e + 1/3 e = +e.

  - The properties of this combination are identical with the π+ meson, and so we identify the π+ with the combination $u\bar{d}$.

Mesons

Combination	Charge (e)	Spin ($\hbar$)	Baryon Number	Strangeness
$u\bar{u}$	0	0, 1	0	0
$u\bar{d}$	+1	0, 1	0	0
$u\bar{s}$	+1	0, 1	0	+1
$d\bar{u}$	−1	0, 1	0	0
$d\bar{d}$	0	0, 1	0	0
$d\bar{s}$	0	0, 1	0	+1
$s\bar{u}$	−1	0, 1	0	−1
$s\bar{d}$	0	0, 1	0	−1
$s\bar{s}$	0	0, 1	0	0

Baryons

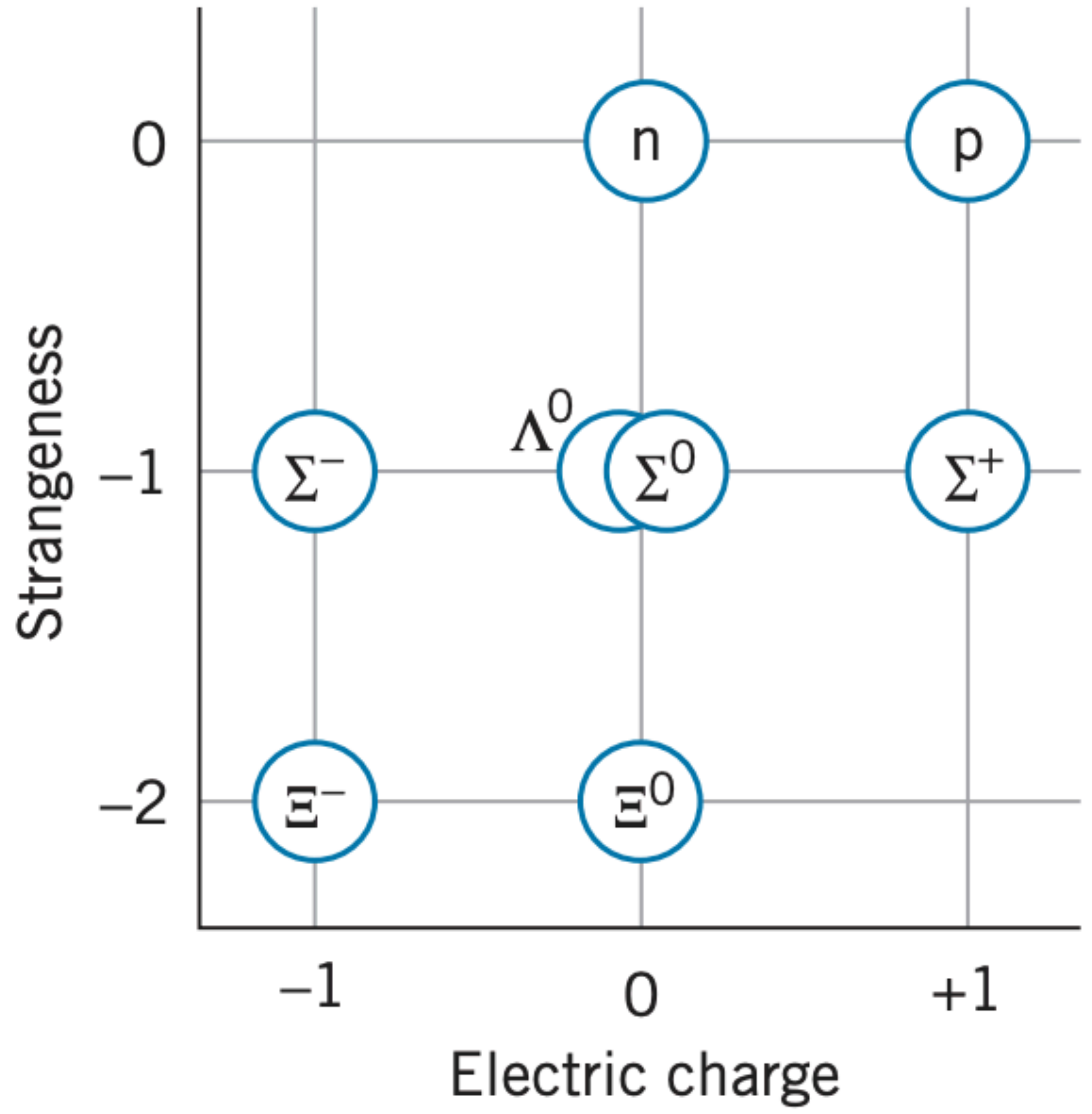


FIGURE 14.12 The relationship between electric charge and strangeness for the spin-$\frac{1}{2}$ baryons.

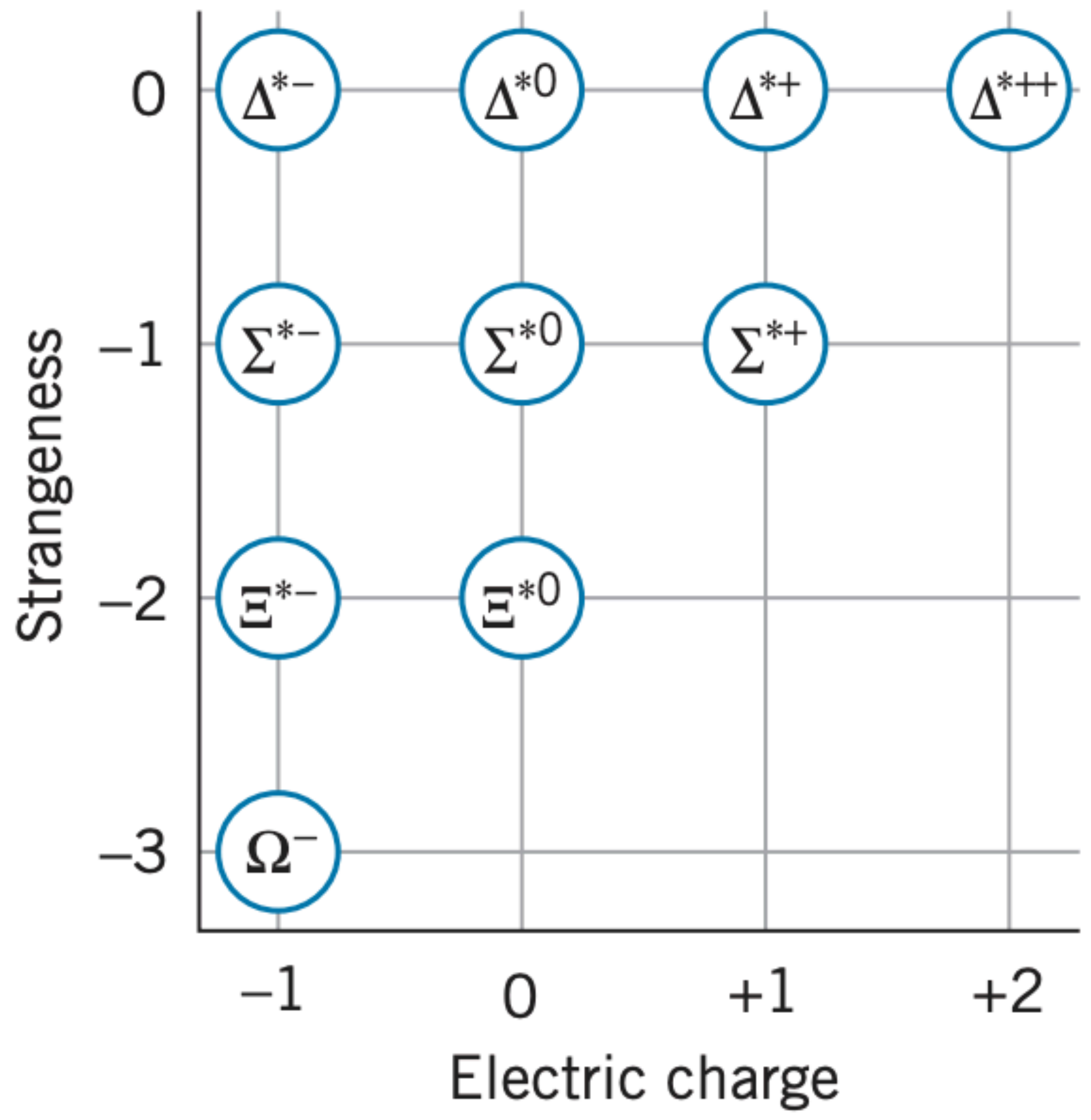


FIGURE 14.13 The relationship between electric charge and strangeness for the spin-$\frac{3}{2}$ baryons.

Baryons

TABLE 14.9 Possible Three-Quark Combinations

Combination	Charge (e)	Spin ($\hbar$)	Baryon Number	Strangeness
uuu	+2	$\frac{3}{2}$	+1	0
uud	+1	$\frac{1}{2}, \frac{3}{2}$	+1	0
udd	0	$\frac{1}{2}, \frac{3}{2}$	+1	0
uus	+1	$\frac{1}{2}, \frac{3}{2}$	+1	−1
uss	0	$\frac{1}{2}, \frac{3}{2}$	+1	−2
uds	0	$\frac{1}{2}, \frac{3}{2}$	+1	−1
ddd	−1	$\frac{3}{2}$	+1	0
dds	−1	$\frac{1}{2}, \frac{3}{2}$	+1	−1
dss	−1	$\frac{1}{2}, \frac{3}{2}$	+1	−2
sss	−1	$\frac{3}{2}$	+1	−3

Baryons

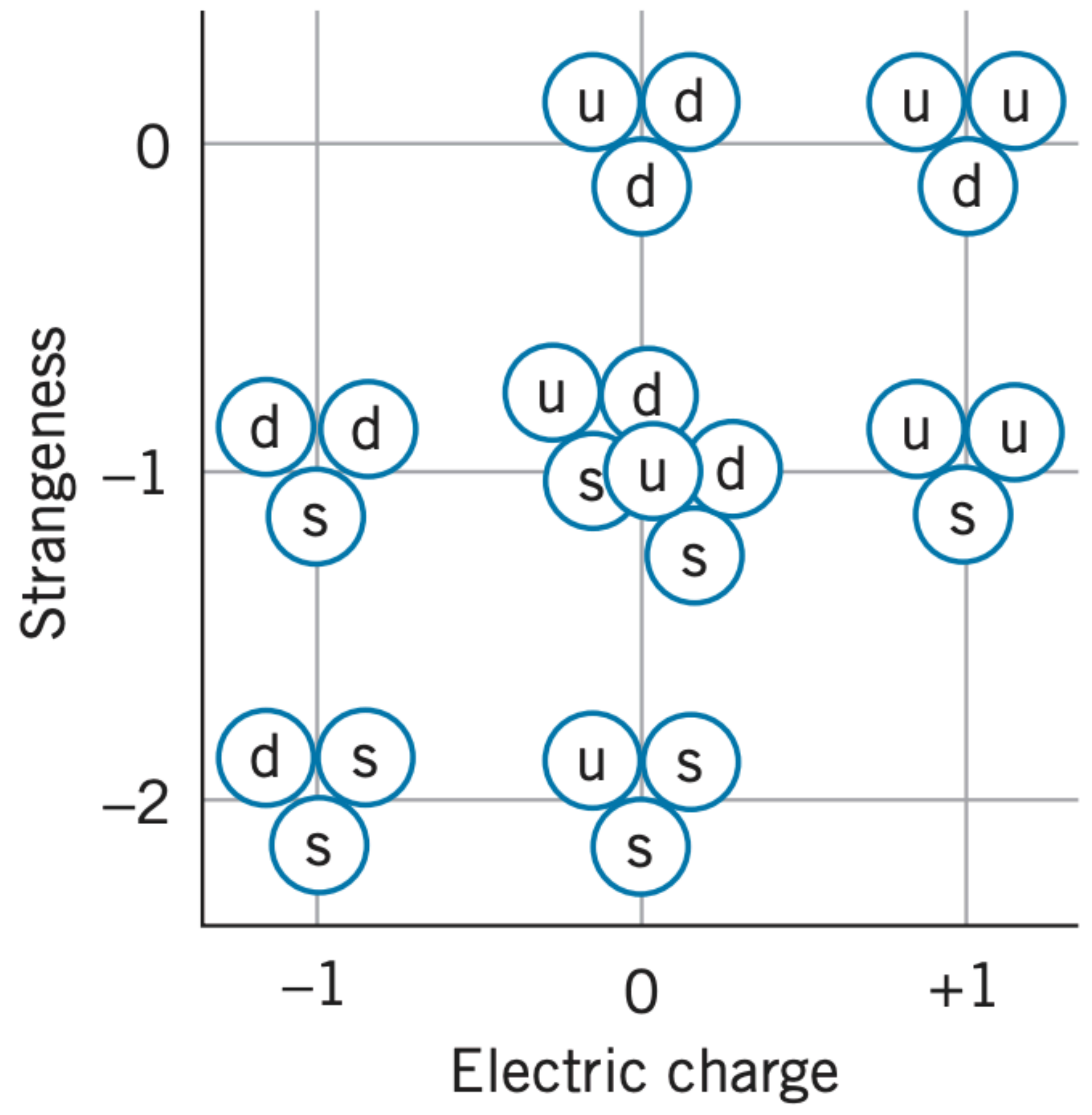


FIGURE 14.15 Spin-$\frac{1}{2}$ three-quark combinations; compare with Figure 14.12.

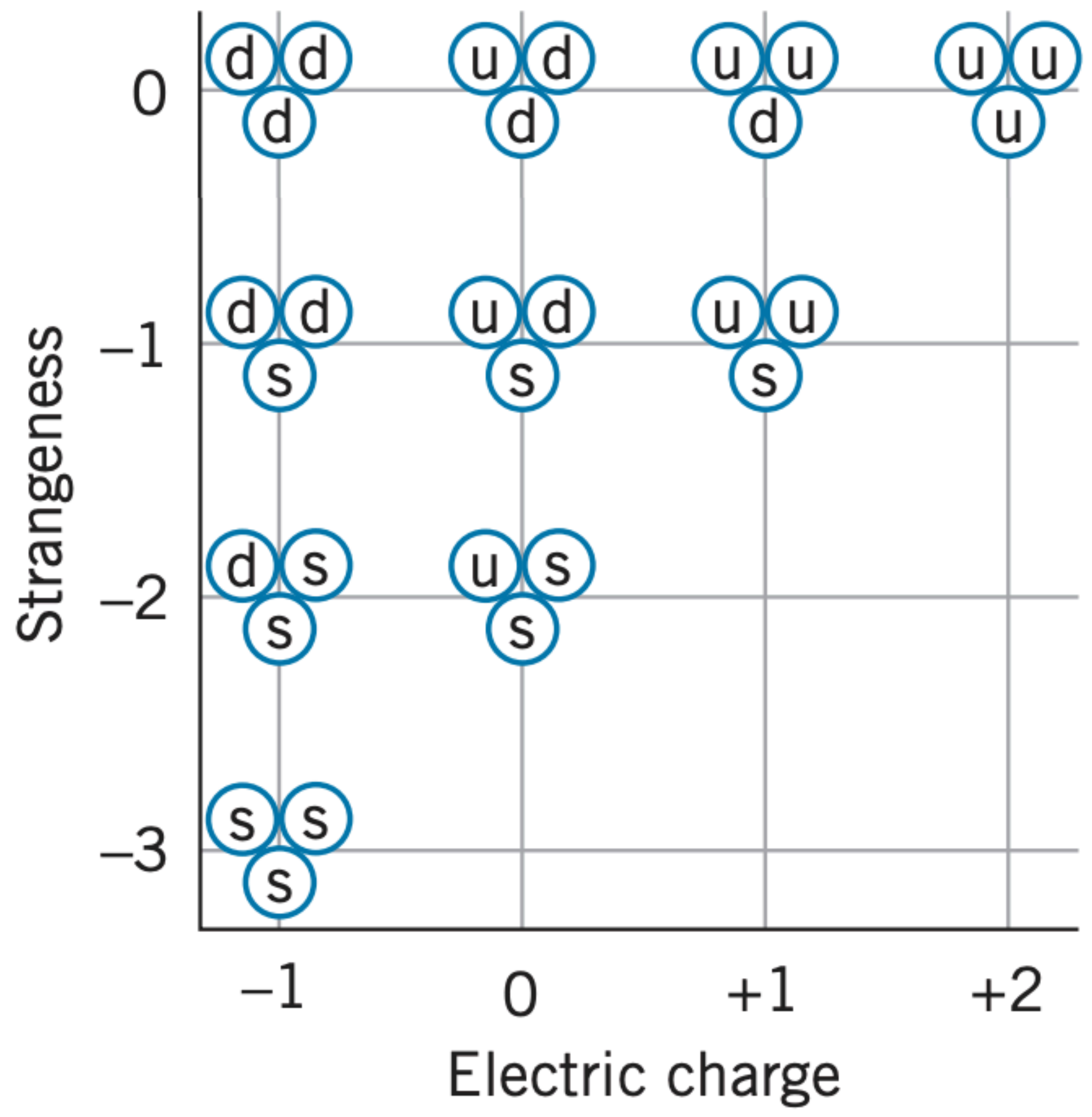


FIGURE 14.16 Spin-$\frac{3}{2}$ three-quark combinations; compare with Figure 14.13.

The Quark Structure of Mesons and Baryons

Using the quark model, we can analyze the decays and reactions of elementary particles, based on two rules:

1. Quark-antiquark pairs can be created from energy quanta, and conversely, can annihilate into energy quanta. For example:

   energy $\rightarrow u + \bar{u}$ or $d + \bar{d} \rightarrow$ energy

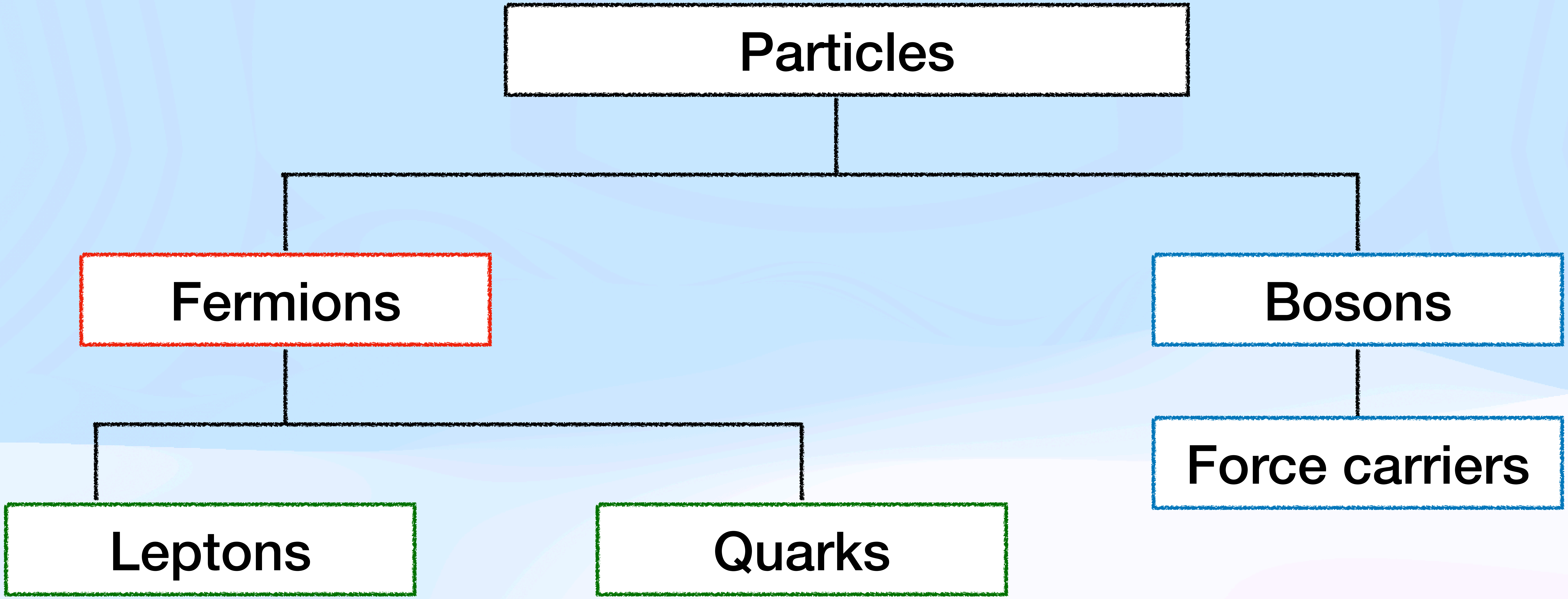
2. The weak interaction can change one type of quark into another through the emission or absorption of a W^+ or W^-, for example, $s \rightarrow u + W^-$. The *W* then decays via the weak interaction $W^- \rightarrow \mu^- + \bar{\nu}_\mu$.
   The strong and electromagnetic interactions cannot change one type of quark into another.

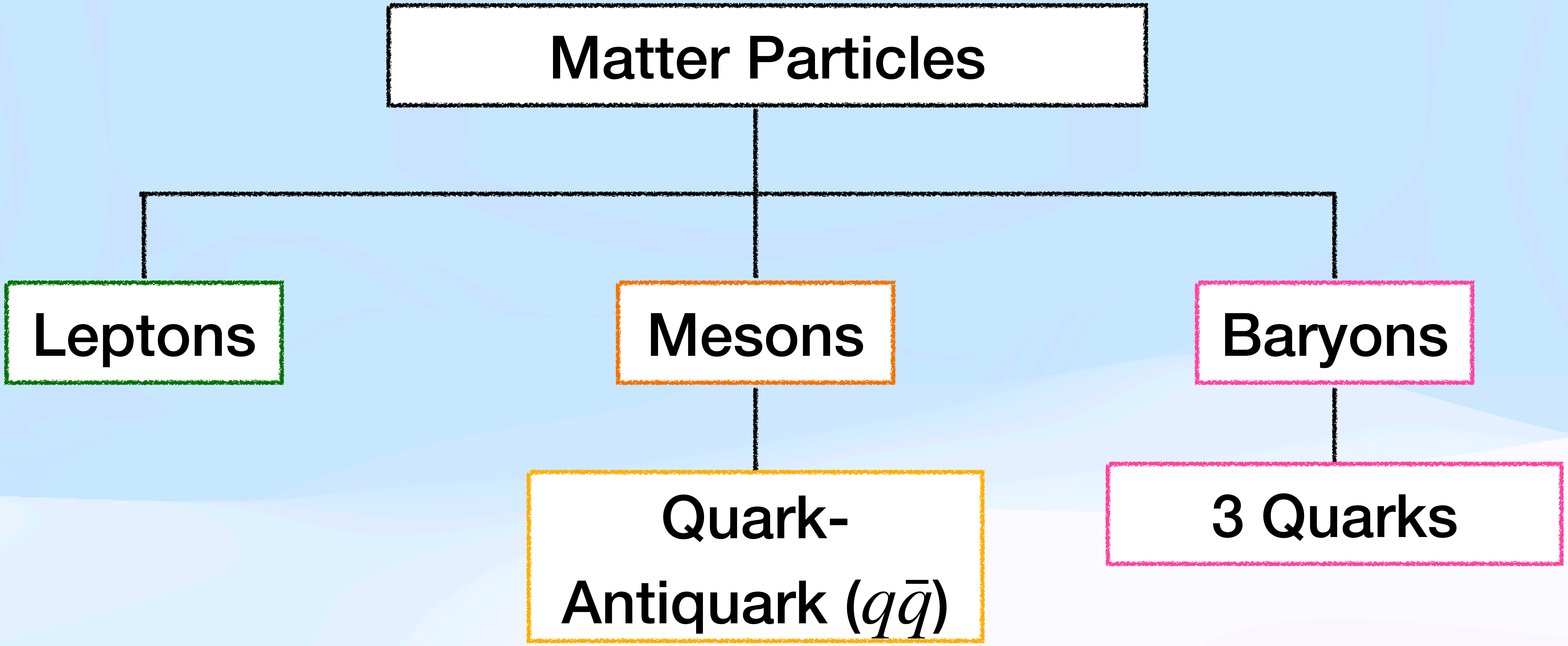
Problem 4

Analyze the following reaction/decay in terms of the constituents quarks:

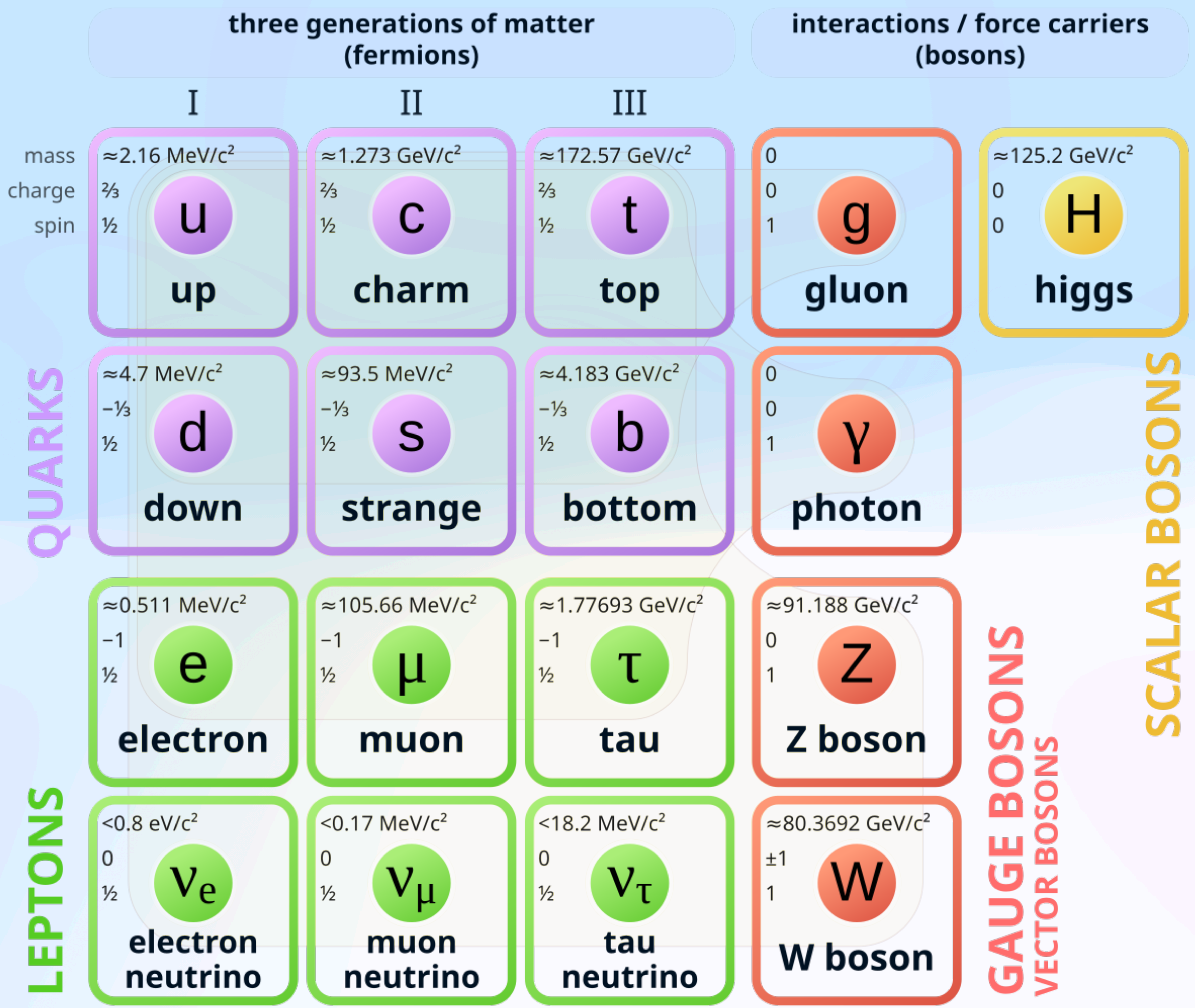
(a) $\pi^- + p \rightarrow K^0 + \Lambda^0$

(b) $\pi^+ \rightarrow \mu^0 + \nu_\mu$

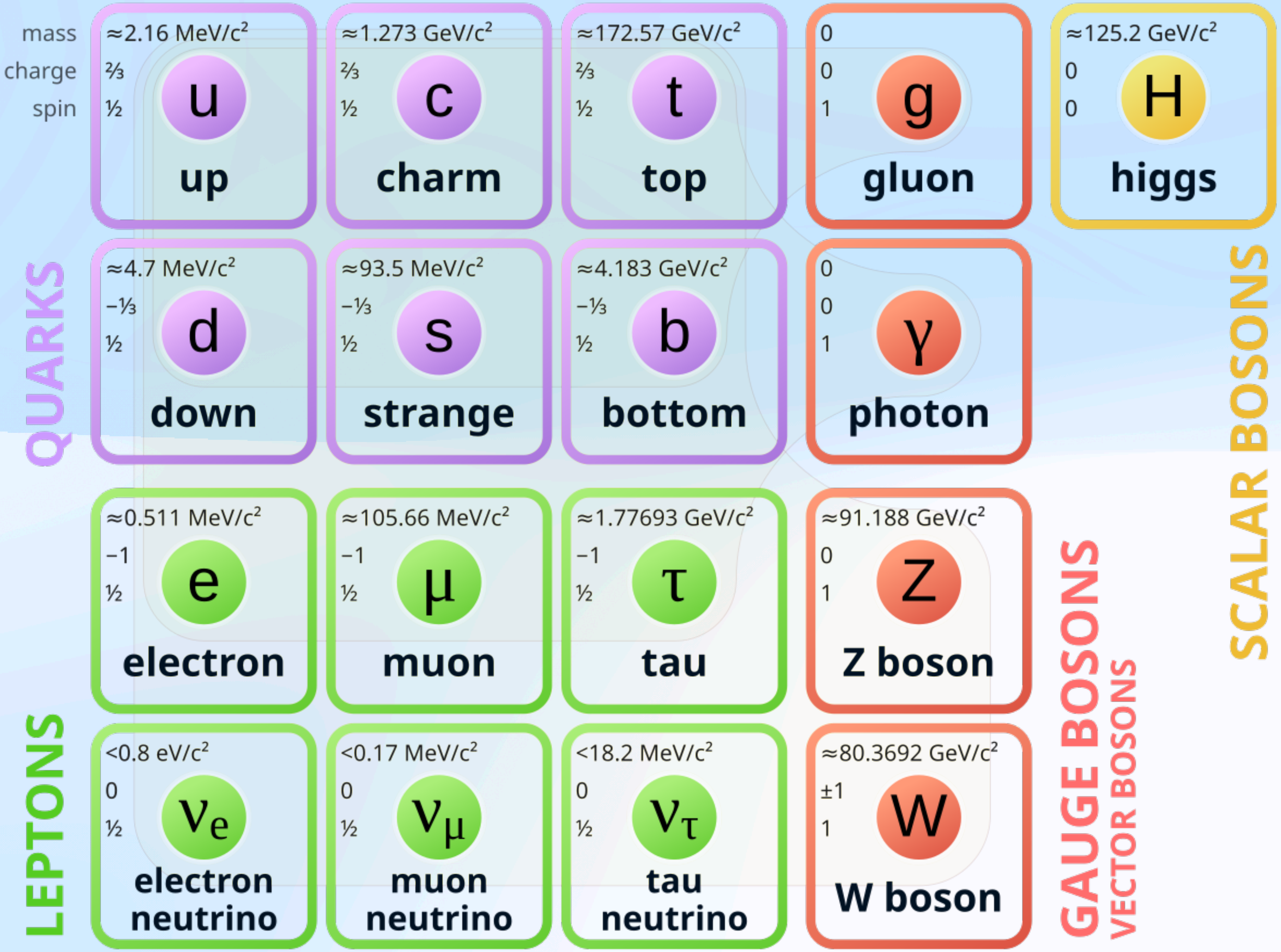

Particles
Fermions
Bosons
Leptons
Quarks
Force carriers


Matter Particles
Leptons
Mesons
Baryons
Quark-Antiquark ($q\bar{q}$)
3 Quarks

Standard Model of Elementary Particles



Standard Model



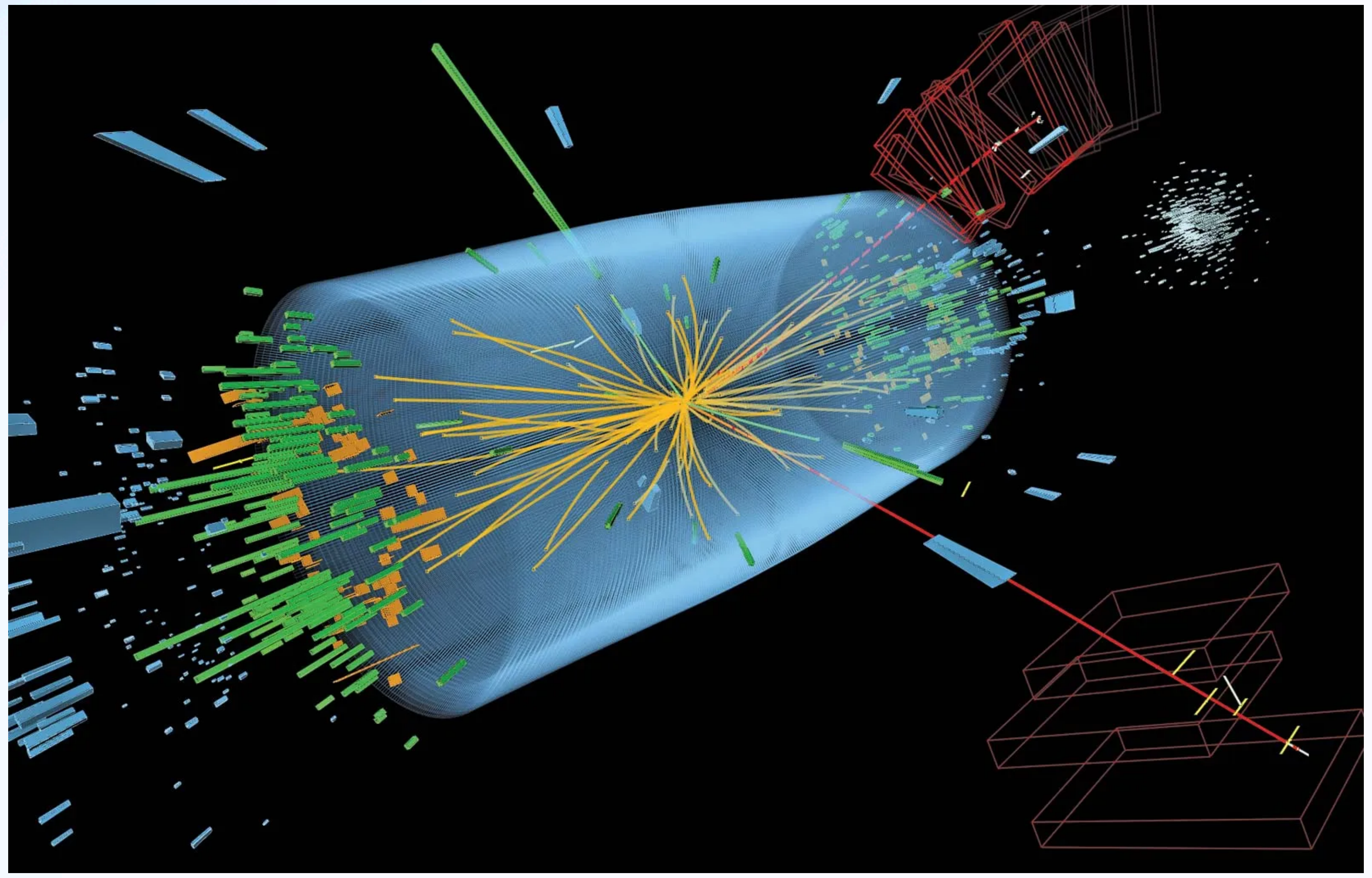
- Can you guess what the next obvious step is from here?

Higgs Boson

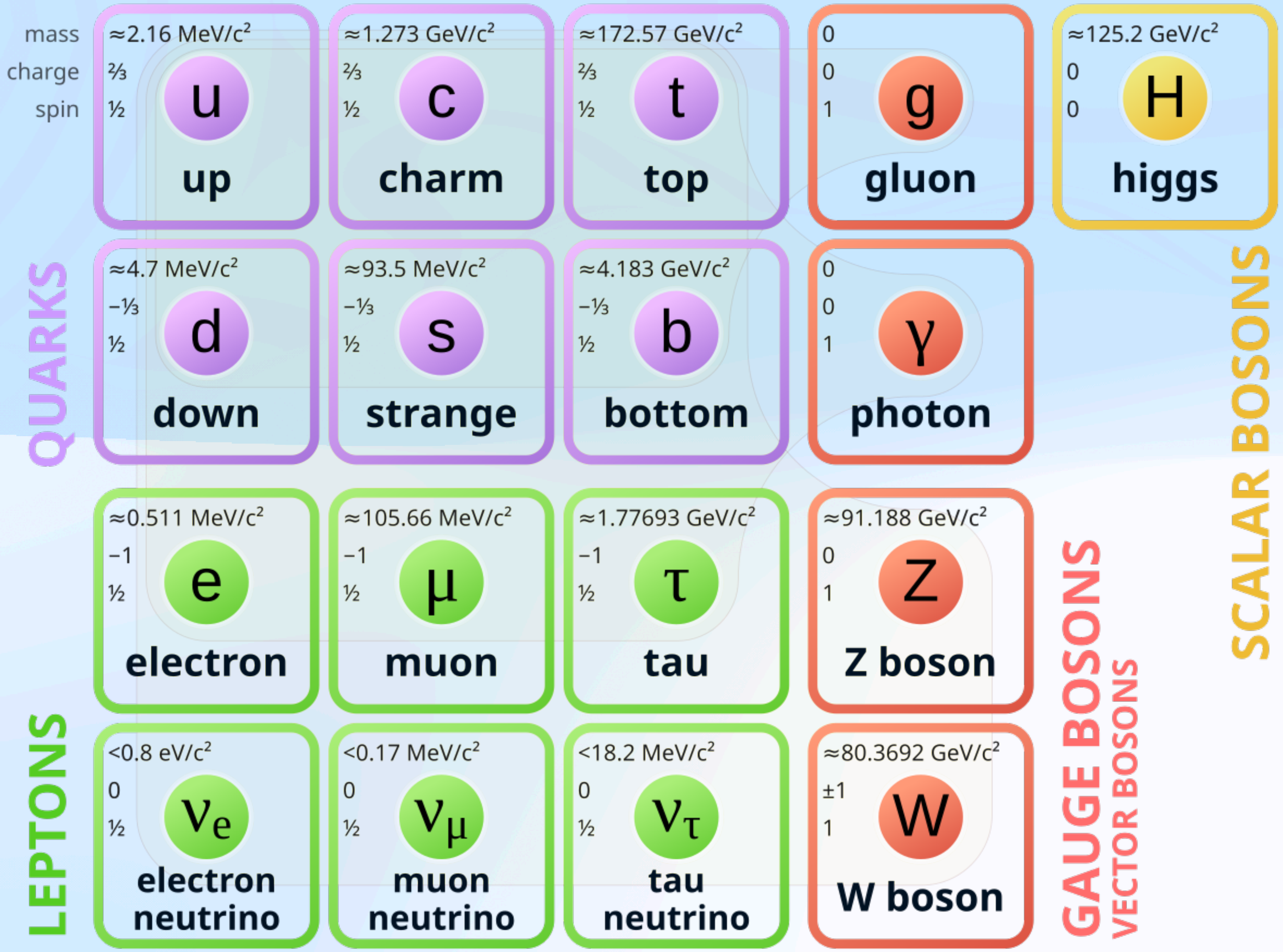
- It’s a very famous boson.
- Some people even call it the God particle
- Why?

Higgs Boson

- In 1964, Peter Higgs proposed that there should be a Higgs field
- This Higgs field has a particle known as the Higgs boson
- This field gives mass to particles, hence the name God particle
- Heavy particles interact more and hence have more mass

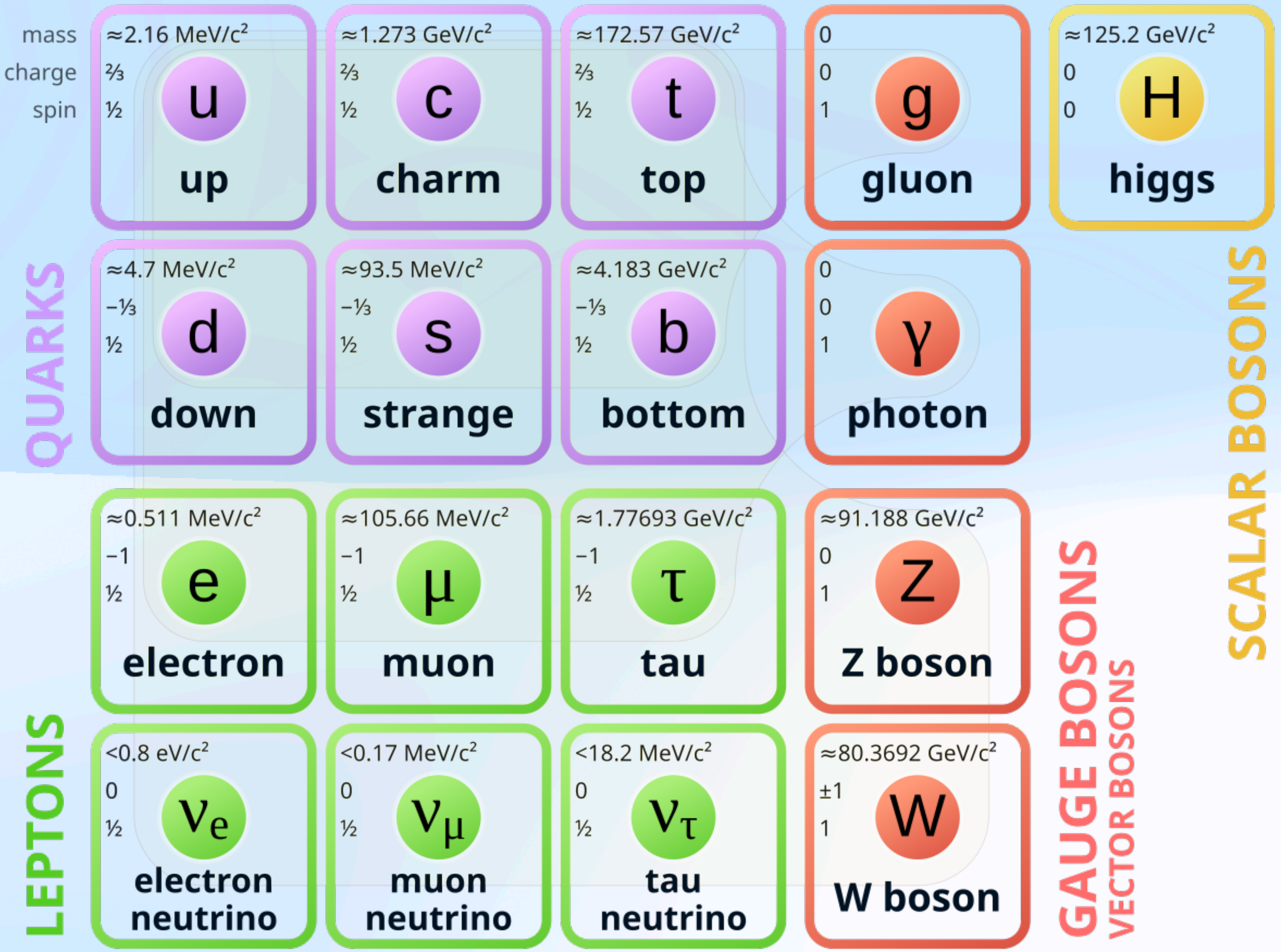


Standard Model



- The Standard Model explains:
  - All known matter particles
  - The **forces** acting between them (except gravity!)
  - But here's a fun twist...
    If the Standard Model is so powerful, how much of the Universe do you think it explains?

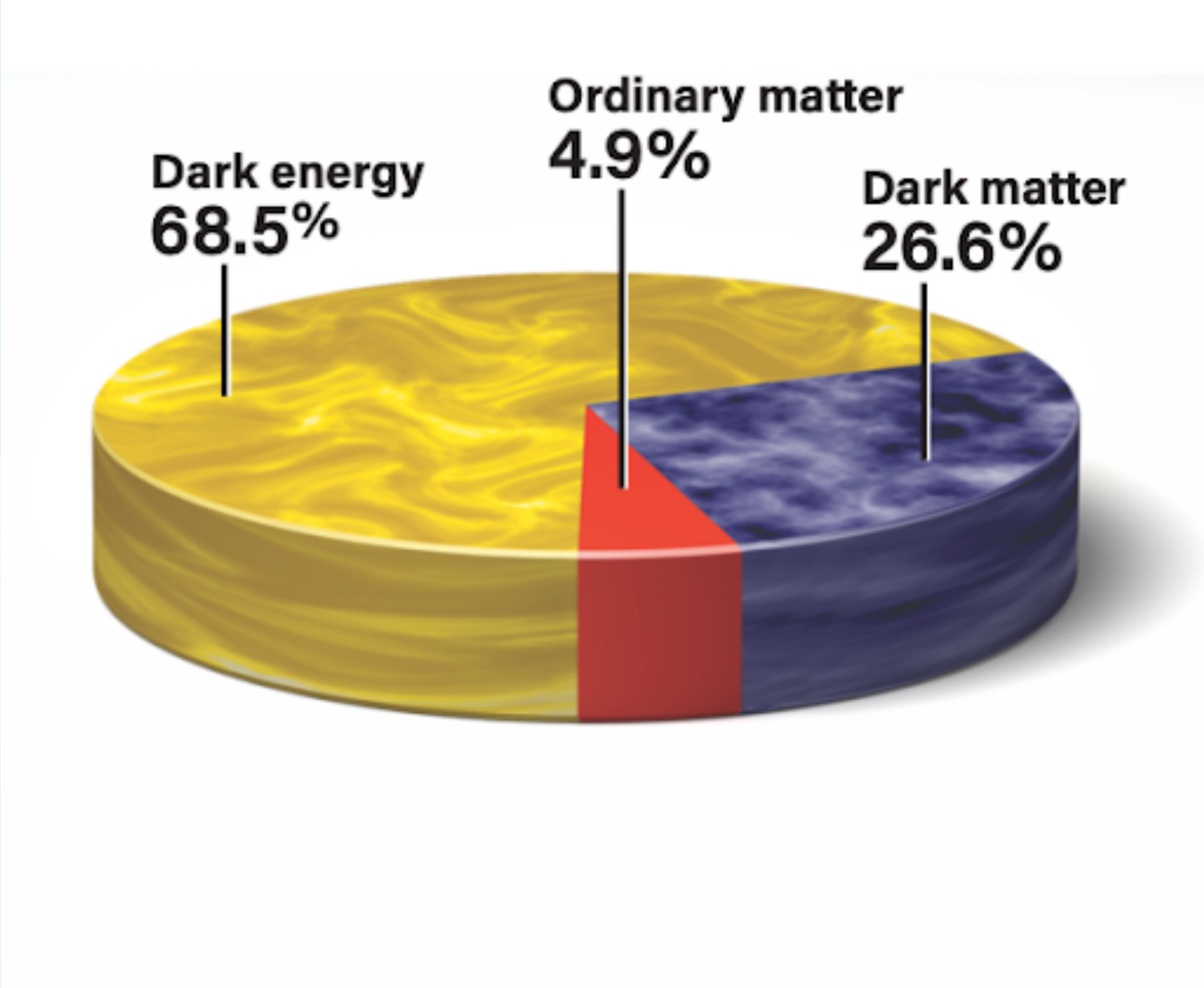
Standard Model



If the Standard Model is so powerful, how much of the Universe do you think it explains?

A. 100%
B. 50%
C. 25%
D. 5%

Standard Model



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