PHYS252 Quantum Physics and Applications

Module 5: Particle Physics

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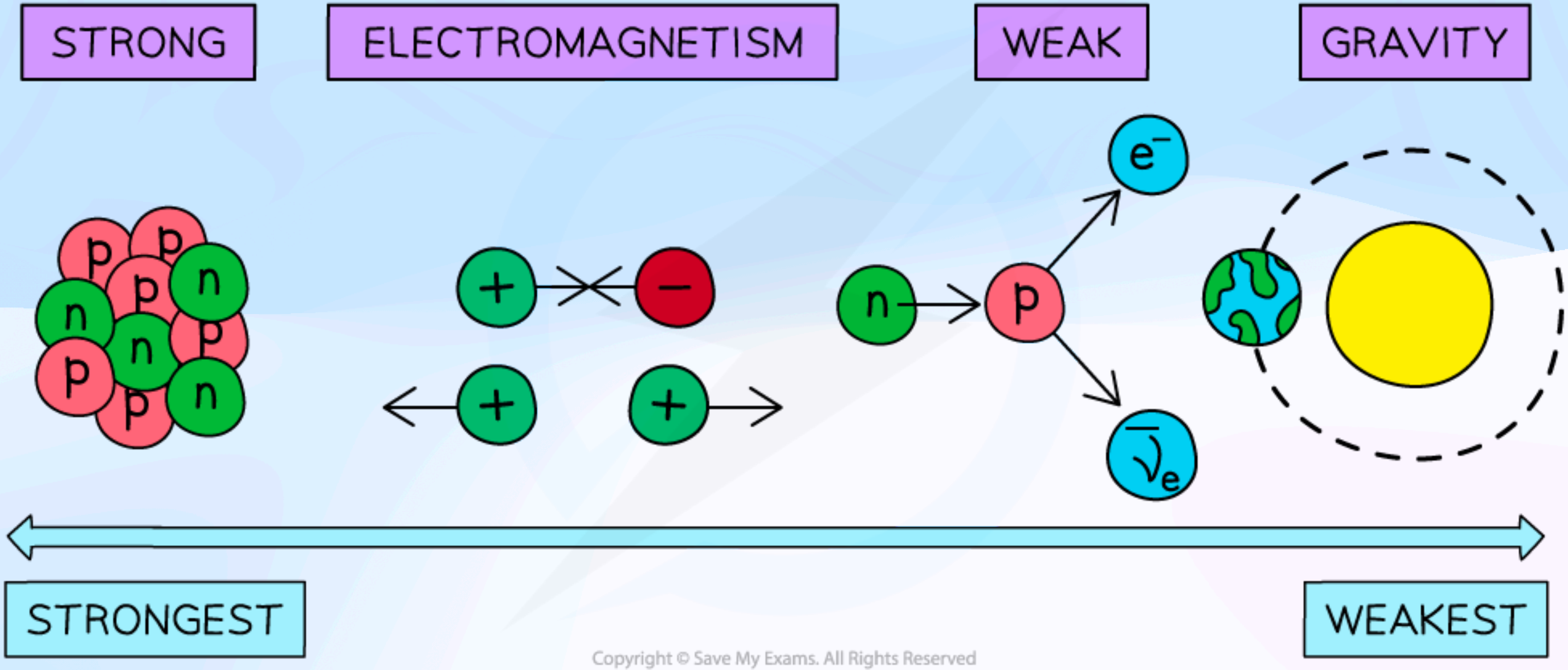
Module 5

- Particle Physics
  - Fundamental Forces
  - Classifying particles
  - Conservations Laws
  - Particle Interactions and Decays
  - Energy and Momentum in Particle Decays
  - Quark Structure
  - Standard Model

Fundamental building blocks

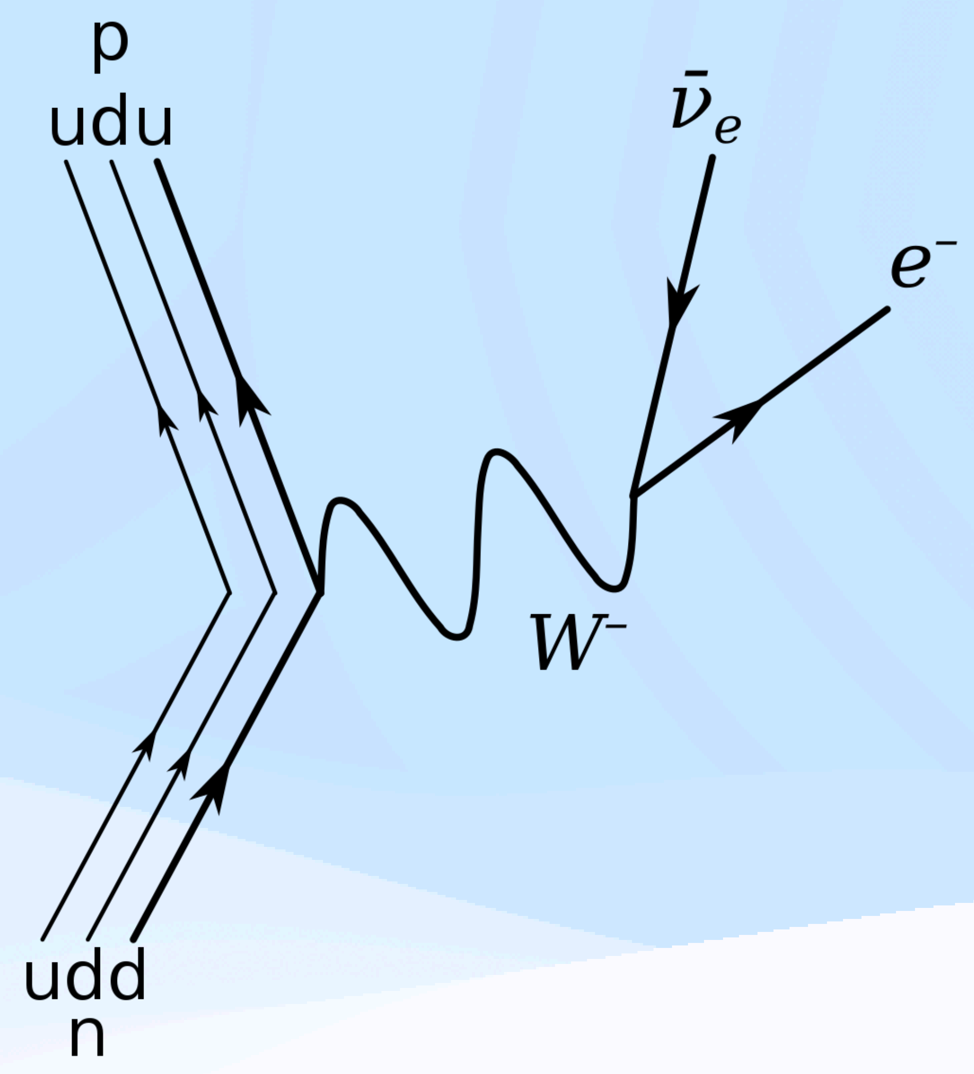
	I	II	III		
mass charge spin					
QUARKS	≈2.16 MeV/c^2 ⅔ ½ u **up**	≈1.273 GeV/c^2 ⅔ ½ c **charm**	≈172.57 GeV/c^2 ⅔ ½ t **top**	0 0 1 g **gluon**	≈125.2 GeV/c^2 0 0 H **higgs**
QUARKS	≈4.7 MeV/c^2 −⅓ ½ d **down**	≈93.5 MeV/c^2 −⅓ ½ s **strange**	≈4.183 GeV/c^2 −⅓ ½ b **bottom**	0 0 1 γ **photon**	
LEPTONS	≈0.511 MeV/c^2 −1 ½ e **electron**	≈105.66 MeV/c^2 −1 ½ μ **muon**	≈1.77693 GeV/c^2 −1 ½ τ **tau**	≈91.188 GeV/c^2 0 1 Z **Z boson**	
LEPTONS	<0.8 eV/c^2 0 ½ ν_e **electron neutrino**	<0.17 MeV/c^2 0 ½ ν_μ **muon neutrino**	<18.2 MeV/c^2 0 ½ ν_τ **tau neutrino**	≈80.3692 GeV/c^2 ±1 1 W **W boson**	
				GAUGE BOSONS VECTOR BOSONS	SCALAR BOSONS

Four Interactions

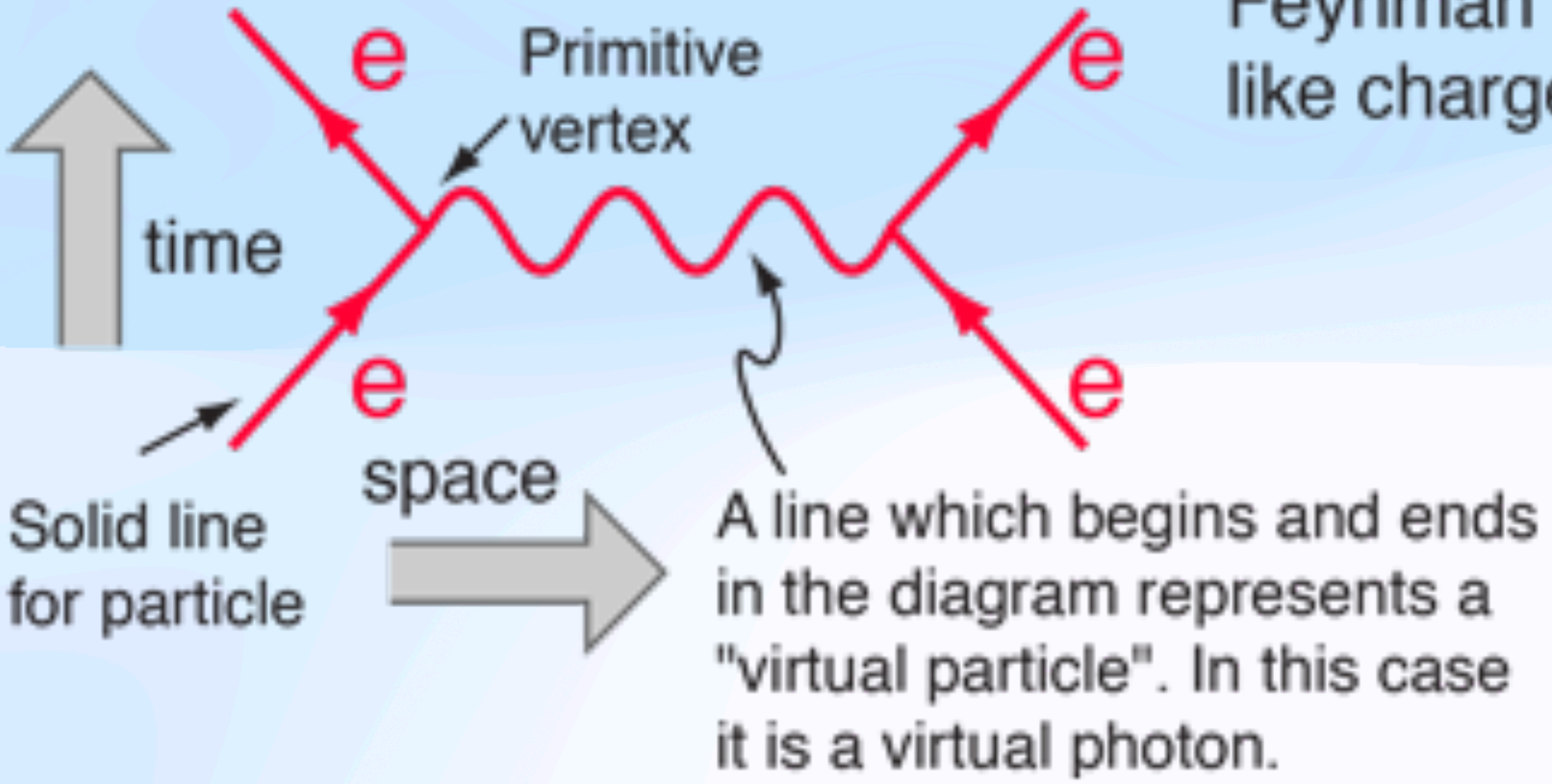


Field Particles

- Field particles are exchanged when there is an interaction (force)
- Field particles are bosons that "carry" the force
- In beta minus decay:
  $n \rightarrow p + W^-$
  violates energy conservation
  - The existence of the W boson is restricted by the uncertainty principle (virtual particle)
  - After some time, we get $W^- \rightarrow e^- + \bar{\nu}$

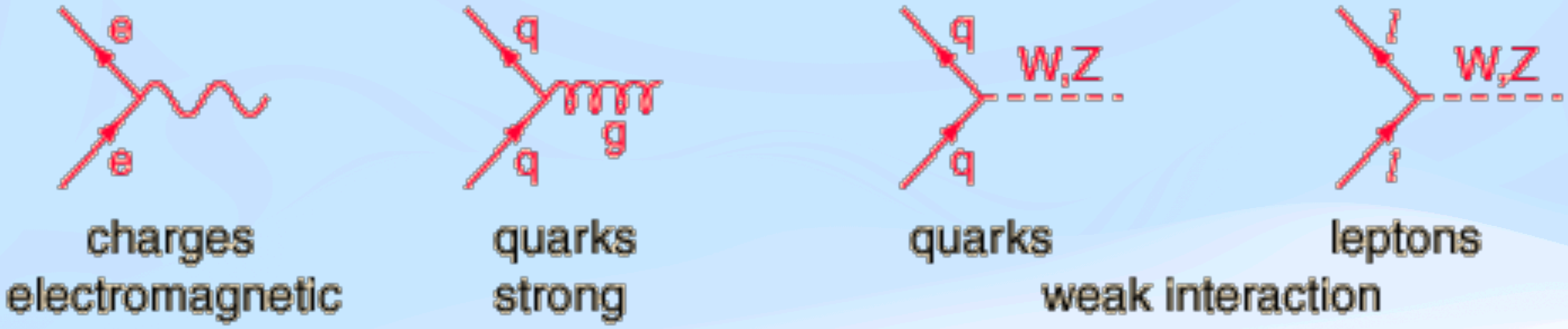


Feynmann Diagrams (Extra understanding, not in the Exam)



Feynman diagram for
like charge repulsion

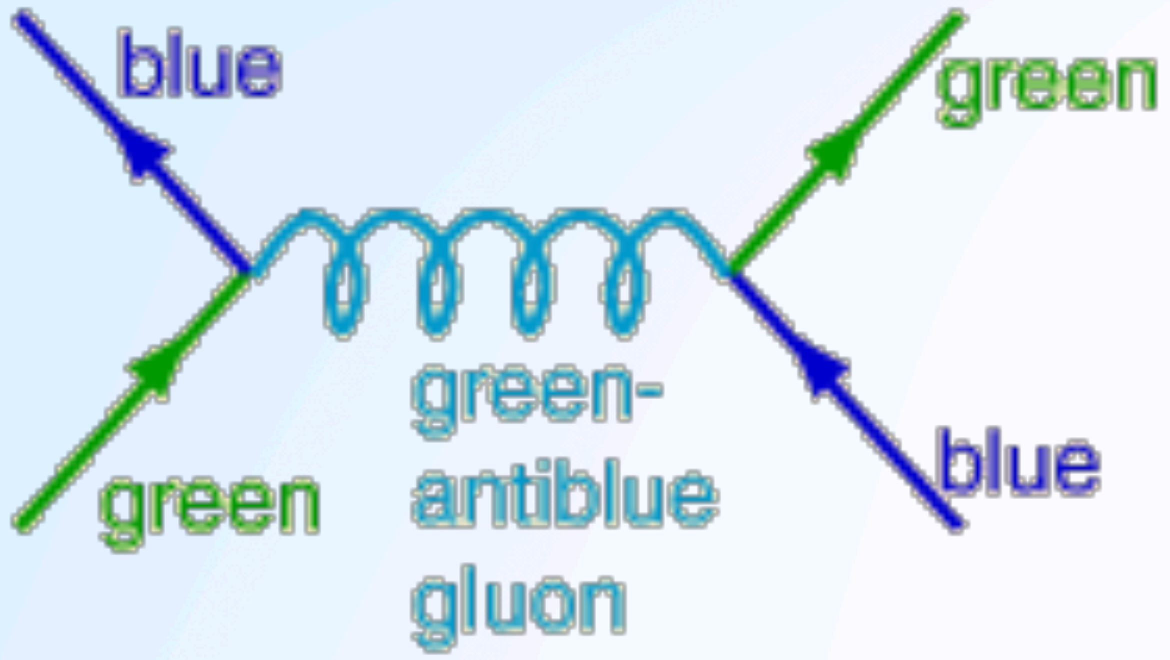
Feynmann Diagrams - Forces



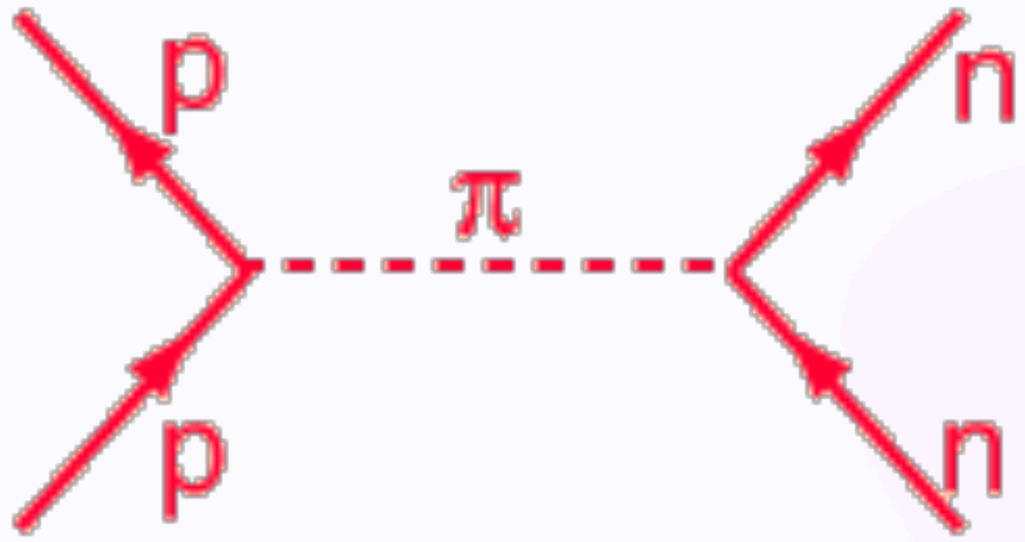
Feynmann Diagrams - Forces

Electromagnetic

Weak



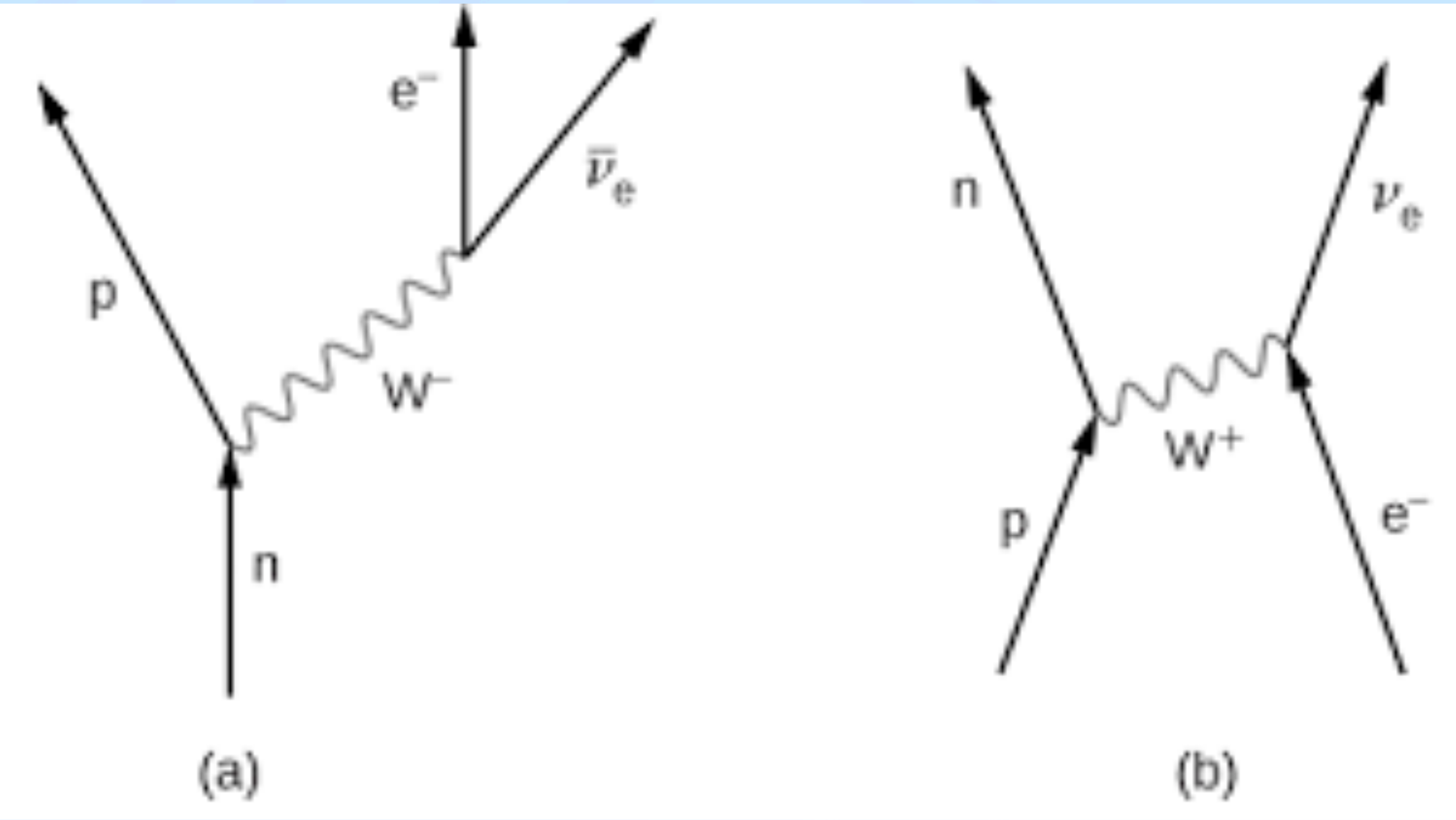
between quarks

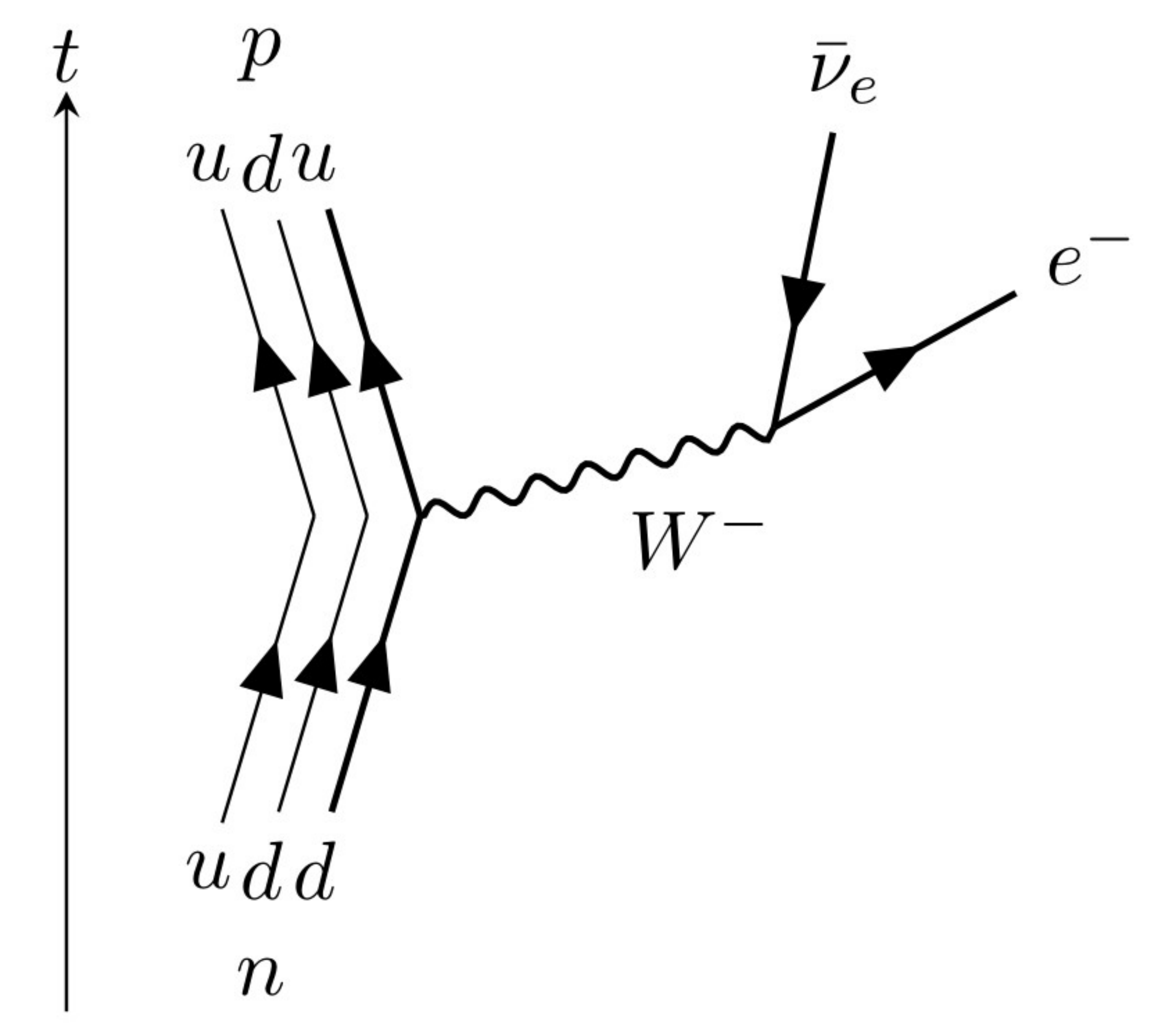


between nucleons

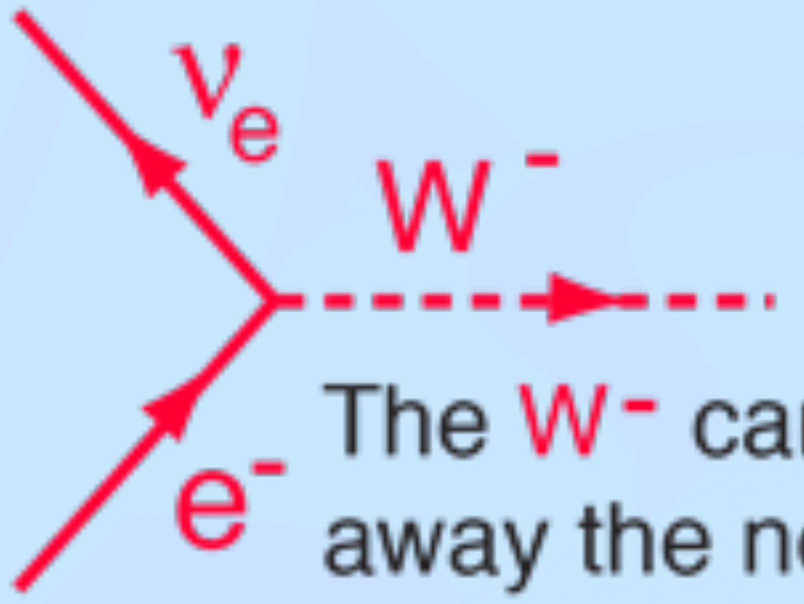
Strong Interaction

Feynmann Diagrams - Beta Decay

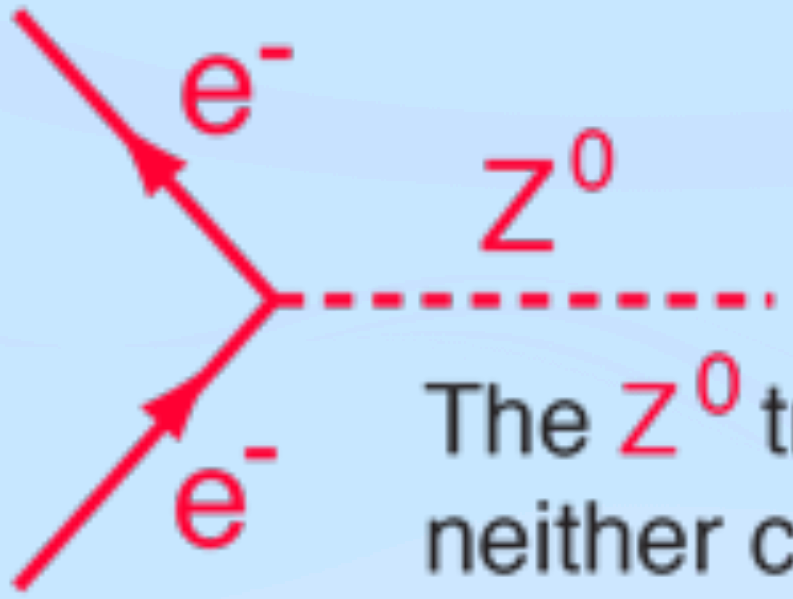




Z Boson



The W^- carries away the negative charge and transforms the electron to an electron neutrino



The Z^0 transforms neither charge nor mass.

Neutral weak interaction

Electromagnetic interaction

Classifying Particles (Chapter 14.2)

- Previously we talked about the field particles that carry each one of the fundamental forces.

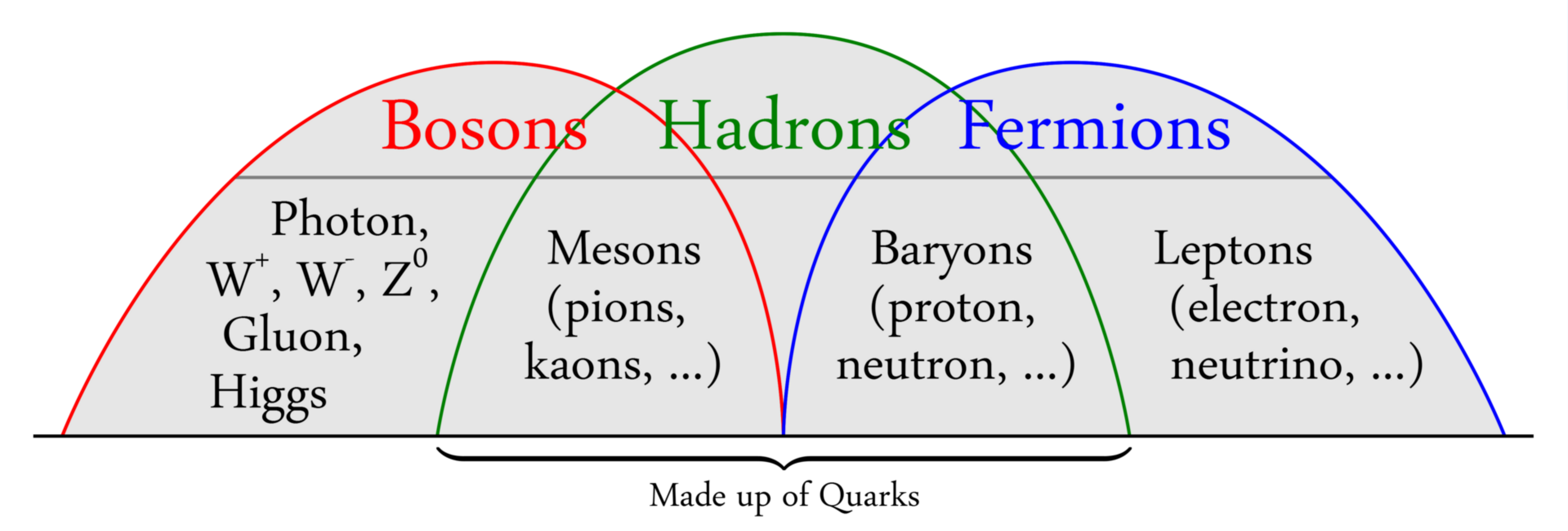
- We want to classify the particles that make the matter around us

- Historically, it was done based on mass:
  - Leptons (*light particles*): includes electrons, muons and neutrons
  - Mesons (middle group): includes pions and kaons
  - Baryons (heavier particles): includes protons and neutrons

  - This classification is obsolete now as leptons and mesons have been discovered which are massive than neutrons and protons

Classifying Particles

- Leptons (fermions)
  - includes electrons, muons, and neutrinos.
  - Do not interact via the strong force.
  - have spin $\frac{1}{2}$
- Baryons (fermions)
  - includes protons and neutrons
  - interact via the strong force
  - half-integer spin e.g. $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \ldots$
- Mesons (bosons)
  - includes pions and kaons.
  - have integer spin.



Classifying Particles

Family	Structure	Interactions	Spin $(\hbar)$	Examples
Leptons	Fundamental	Weak, electromagnetic	$\frac{1}{2}$	e, υ
Mesons	Composite	Weak, strong electromagnetic	Integral	π, K
Baryons	Composite	Weak, strong electromagnetic	Half Integral	p, n

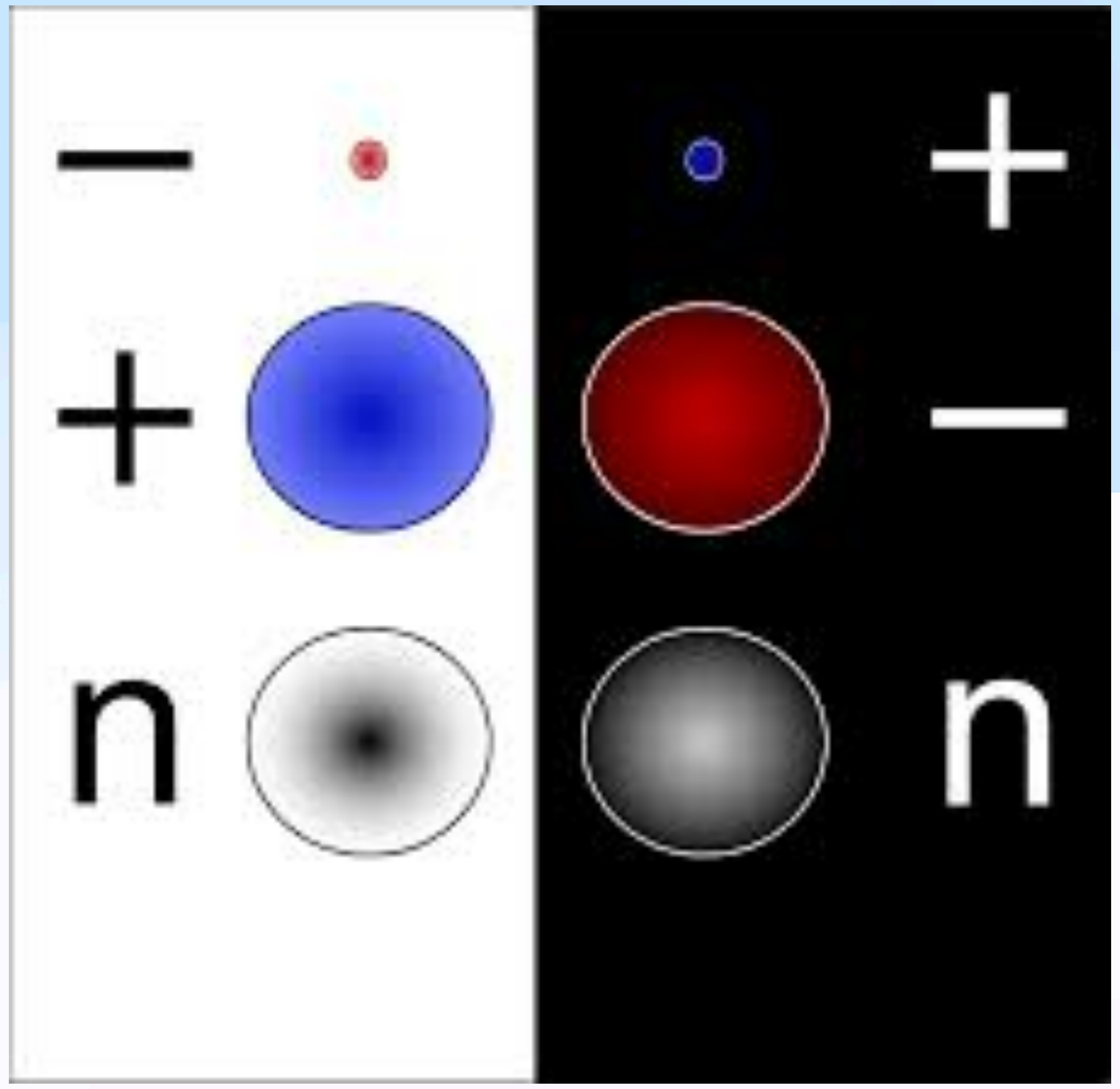
The term hadron refers to any particle that is made from quarks and includes Mesons and Baryons.

Anti-particles

- Every particle has an antiparticle that has identical mass and lifetime, but the opposite sign of electric charge.

- The positron, e^+, was discovered the 1930s. It has a charge of $+e$ and a mass of 0.511 MeV.

- The antiproton, $\bar{p}$, was discovered in 1956, with a charge of $-e$ and a mass of 938 MeV.



Anti-particles

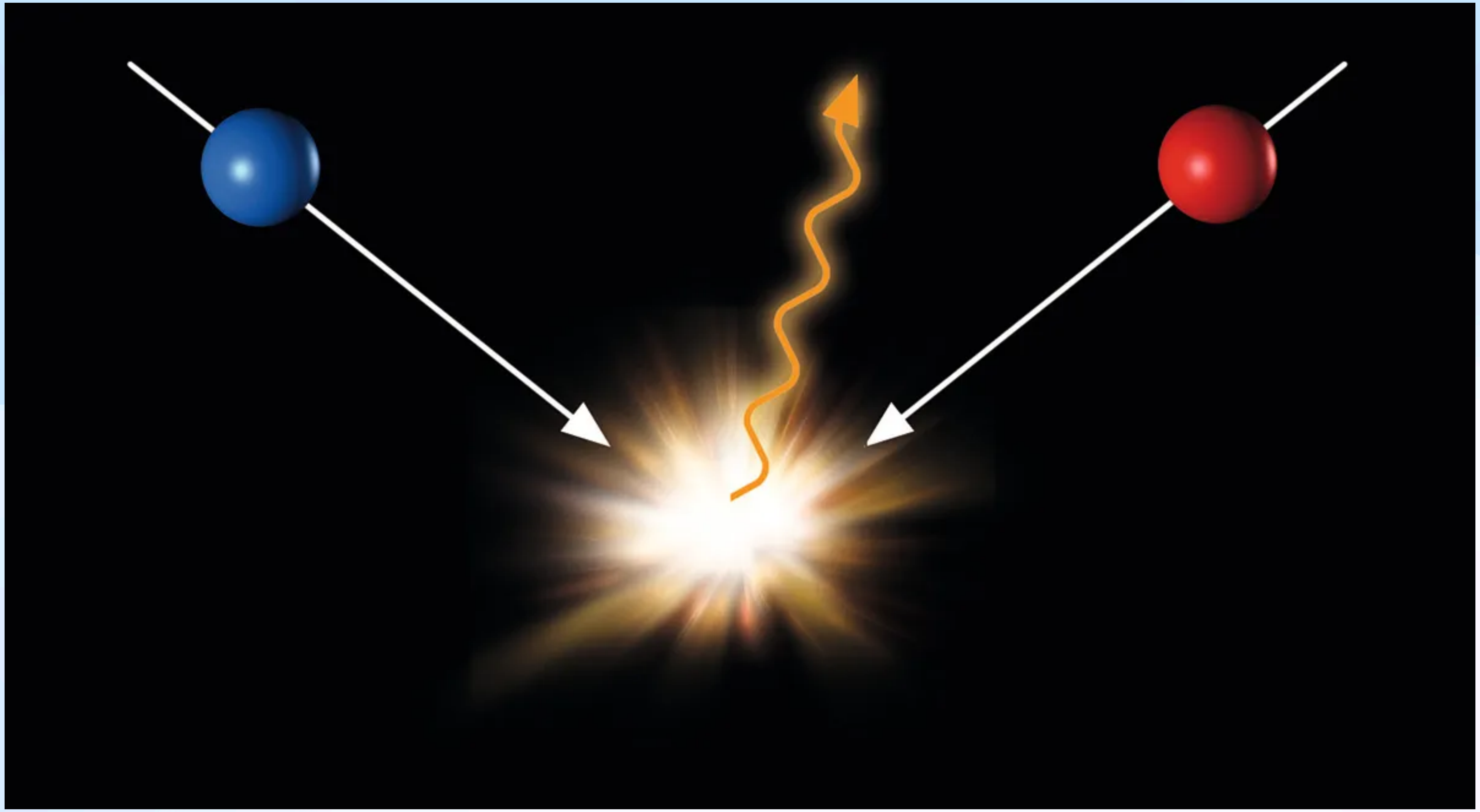
- Antiparticles of stable particles are themselves stable.

- However, when a particle and an antiparticle collide, they can annihilate, emitting two photons with energy equal to the rest mass of each particle.

$$e^- + e^+ \rightarrow \gamma_1 + \gamma_2 \qquad \left(E_{\gamma_1} = E_{\gamma_2} = 0.511\ MeV\right)$$

$$p + \bar{p} \rightarrow \gamma_1 + \gamma_2 \qquad \left(E_{\gamma_1} = E_{\gamma_2} = 938\ MeV\right)$$

Anti-particles



Anti-particles

- We call the kind of stuff of which we are made matter and the other kind of stuff antimatter.

- There may indeed be galaxies composed of antimatter, but we cannot tell by the ordinary astronomy techniques, because light and antilight are identical!

- In other words, the photon and antiphoton are the same particles, so matter and antimatter emit the same photons.

Anti-particles

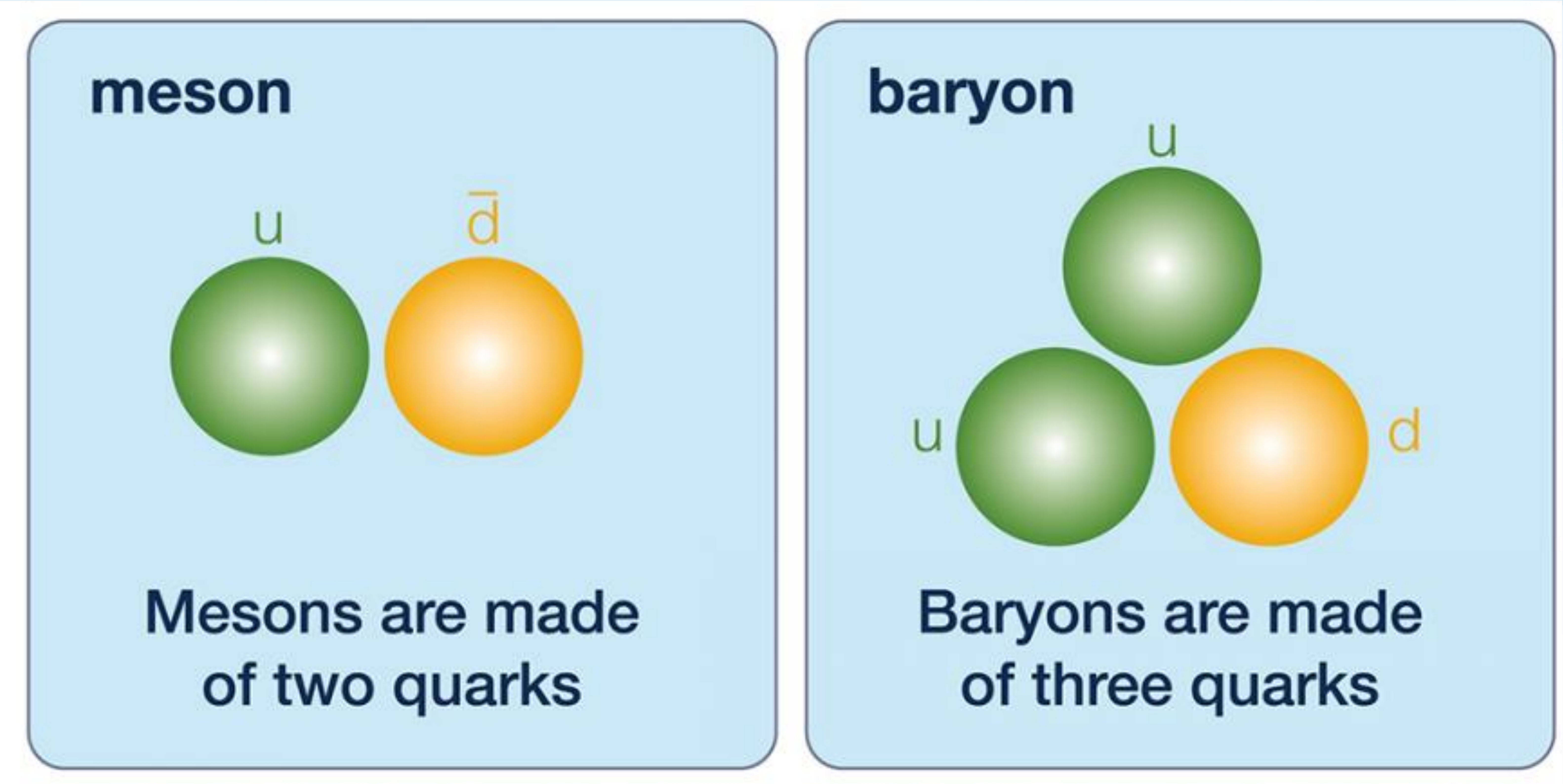
- The only way to tell the difference is by sending a chunk of our matter to a distant galaxy and seeing whether or not it is annihilated with the corresponding emission of a burst of photons.
- It is indeed possible, but highly unlikely, that the first astronaut to travel to another galaxy may suffer such a fate! The first intergalactic handshake would indeed be quite an event!

Leptons

Particle	Anti-particle	Particle Charge (e)	Rest Energy (MeV)	Mean Life (s)	Typical Decay Products
e^-	e^+	-1	0.511	∞	
υ_e	$\overline{\upsilon_e}$	0	$< 0.12\ eV$	∞	
μ^-	μ^+	-1	105.7	2.2×10^{-6}	$e^- + \overline{\upsilon_e} + \upsilon_\mu$
υ_μ	$\overline{\upsilon_\mu}$	0	$< 0.12\ eV$	∞	
τ^-	τ^+	-1	1776.9	2.9×10^{-13}	$\mu^- + \overline{\upsilon_\mu} + \upsilon_\tau$
υ_τ	$\overline{\upsilon_\tau}$	0	$< 0.12\ eV$	∞	

Mesons and Baryons

- Mesons and Baryons are composite particles
- Mesons are made from quark-antiquark pairs, e.g., $u\bar{u}$, $s\bar{s}$, $u\bar{d}$



Some Selected Mesons

Particle	Anti-particle	Particle Charge (e)	Spin $(\hbar)$	Rest Energy (MeV)	Mean Life (s)	Typical Decay Products
π^+	π^-	+1	0	140	2.6×10^{-8}	$\mu^+ + \upsilon_\mu$
π^0	π^0	0	0	135	8.5×10^{-17}	$\gamma + \gamma$
K^+	K^-	+1	0	494	1.2×10^{-8}	$\mu^+ + \upsilon_\mu$
K^0	$\bar{K}^0$	0	0	498	0.9×10^{-10}	$\pi^+ + \pi^-$
ρ^+	ρ^-	+1	1	775	4.4×10^{-24}	$\pi^+ + \pi^0$
J/ψ	J/ψ	0	1	3097	7.1×10^{-21}	$e^+ + e^-$

Some Selected Baryons

Particle	Anti-particle	Particle Charge (e)	Spin $(\hbar)$	Rest Energy (MeV)	Mean Life (s)	Typical Decay Products
p	$\bar{p}$	+1	$\frac{1}{2}$	938	∞	
n	$\bar{n}$	0	$\frac{1}{2}$	940	880	$p + e^{-} + \bar{\upsilon}_e$
Λ^0	$\overline{\Lambda}^0$	0	$\frac{1}{2}$	1116	2.6×10^{-10}	$p + \pi^{-}$
Ω^{-}	$\overline{\Omega}^{-}$	-1	$\frac{3}{2}$	1672	8.2×10^{-11}	$\Lambda^0 + K^{-}$

Conservation Laws (Chapter 14.3)

- Decays and reactions of elementary particles must satisfy conservation laws
  - Energy and momentum conservation
  - Lepton number conservation
  - Baryon number conservation
  - Strangeness conservation

Conservation Laws: Lepton

- **Lepton number conservation**

The electron and neutrino are assigned lepton numbers, $L = +1$, and the positron and antineutrino are assigned lepton numbers, $L = -1$.

$$n \to \; p + e^- + \bar{\nu}_e \qquad\qquad p \to \; n + \; e^+ + \; \nu_e$$

$$L: 0 \;\to\; 0 + 1 + (-1) \qquad\qquad L: 0 \;\to\; 0 + (-1) + 1$$

In any process, the lepton numbers for electron-type, muon-type, and two-type leptons much each remain constant.

Conservation Laws: Lepton

$$
\begin{array}{rccccccccc}
 & \bar{\nu}_e & + & p & \rightarrow & e^+ & + & n \\
L_e: & -1 & + & 0 & \rightarrow & -1 & + & 0
\end{array}
$$

$$
\begin{array}{rccccccccc}
 & \nu_\mu & + & n & \rightarrow & \mu^- & + & p \\
L_\mu: & 1 & + & 0 & \rightarrow & 1 & + & 0
\end{array}
$$

$$
\begin{array}{rccccccccc}
 & \mu^- & \rightarrow & e^- & + & \bar{\nu}_e & + & \nu_\mu \\
L_e: & 0 & \rightarrow & 1 & + & (-1) & + & 0 \\
L_\mu: & 1 & \rightarrow & 0 & + & 0 & + & 1
\end{array}
$$

$$
\begin{array}{rccccc}
 & \pi^- & \rightarrow & \mu^- & + & \bar{\nu}_\mu \\
L_\mu: & 0 & \rightarrow & 1 & + & (-1)
\end{array}
$$

This is the reason why sometimes neutrinos appear and sometimes antineutrinos appear

Conservation Laws: Baryons

In any process, the total baryon number must be constant.

Baryons are assigned, $B = +1$, and antibaryons are assigned $\mathrm{B} = -1$. The conservation of mass number, A, is a special case in which all the baryons are nucleons. Proton decay would violate baryon number conservation.

The antiproton was discovered in the following reaction:

$$p + p \rightarrow \quad p + p + p + \bar{p}$$

The total baryon number $\mathrm{B} = 2$.

Conservation Laws: Strangeness

The number of mesons that can be created or destroyed in decays or reactions is not subject to a conservation law like the number of leptons or baryons. There just must be enough energy to make the particles.

$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{n} + \pi^{+} \qquad \mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{n} + \pi^{+} + \pi^{0}$$

$$\mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{p} + \pi^{0} \qquad \mathrm{p} + \mathrm{p} \rightarrow \mathrm{p} + \mathrm{p} + \pi^{+} + \pi^{-}$$

As long as enough energy is available, any number of pions can be produced in these reactions.

Conservation Laws: Strangeness

Can we do the same to produce K mesons?

Particle	Anti-particle	Particle Charge (e)	Spin $(\hbar)$	Rest Energy (MeV)	Mean Life (s)	Typical Decay Products
π^+	π^-	+1	0	140	2.6×10^{-8}	$\mu^+ + \upsilon_\mu$
π^0	π^0	0	0	135	8.5×10^{-17}	$\gamma + \gamma$
K^+	K^-	+1	0	494	1.2×10^{-8}	$\mu^+ + \upsilon_\mu$
K^0	$\overline{K}^0$	0	0	498	0.9×10^{-10}	$\pi^+ + \pi^-$

Conservation Laws: Strangeness

Can we do the same to produce K mesons?

- These reactions CANNOT occur,
  $p + p \rightarrow p + n + K^{+}$ and $p + p \rightarrow p + p + K^{0}$
  even if the incident photon have enough energy to produce this particle

- However, we can have these
  $p + p \rightarrow p + n + K^{+} + \bar{K}^{0}$ and $p + p \rightarrow p + p + K^{+} + K^{-}$

- **Why with π mesons we can get any number but with K meson, we only get in pairs?**

Conservation Laws: Strangeness

- Another unusual example:
  - $\pi^- + \mathrm{p} \rightarrow \pi^+ + \Sigma^-$ (another type of baryon) preserves electric charge and baryon number

Does not occur

  - $\pi^- + \mathrm{p} \rightarrow \mathrm{K}^+ + \Sigma^-$

Does occurs

Conservation Laws: Strangeness

- Another unusual example:
  - $\pi^- + \mathrm{p} \rightarrow \pi^+ + \Sigma^-$ (another type of baryon) preserves electric charge and baryon number

    Does not occur

  - $\pi^- + \mathrm{p} \rightarrow \mathrm{K}^+ + \Sigma^-$

    Does occurs

Is there a new conserved quantity whose violation prohibits the reaction from occurring?

Conservation Laws: Strangeness

- We can explain all of this with a quantity known as strangeness S

Particle	Antiparticle	Charge* (e)	Spin ($\hbar$)	Strangeness*	Rest Energy (MeV)	Mean Life (s)	Typical Decay Products
π^+	π^-	+1	0	0	140	2.6×10^{-8}	$\mu^+ + \nu_\mu$
π^0	π^0	0	0	0	135	8.4×10^{-17}	$\gamma + \gamma$
K^+	K^-	+1	0	+1	494	1.2×10^{-8}	$\mu^+ + \nu_\mu$
K^0	$\overline{K}^0$	0	0	+1	498	0.9×10^{-10}	$\pi^+ + \pi^-$

Conservation Laws: Strangeness

- We can explain all of this with a quantity known as strangeness S

The total strangeness must remain constant in processes governed by the strong or electromagnetic interactions.

$K^+ \rightarrow \pi^+ + \pi^0$ can occur despite breaking strangeness conservation, but on a time scale too slow to be strong. This is a weak interaction.

In processes governed by the weak interaction, the strangeness either remains constant or changes by on unit.

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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$$\mathbf{K}^- + \mathbf{p} \rightarrow \Sigma^- + ?$$

Problem 1

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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

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

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

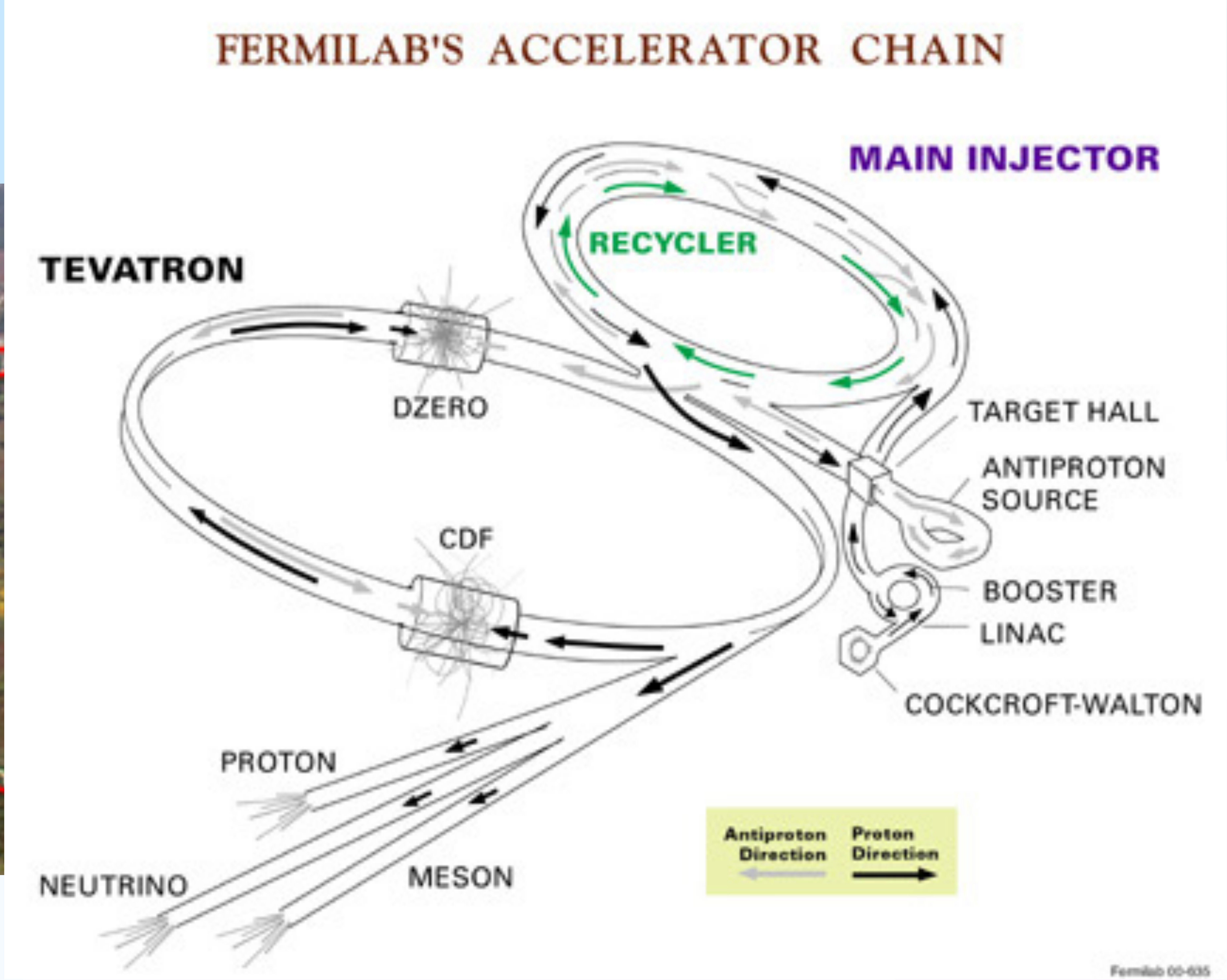
Particle Interactions and Decay

- 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

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

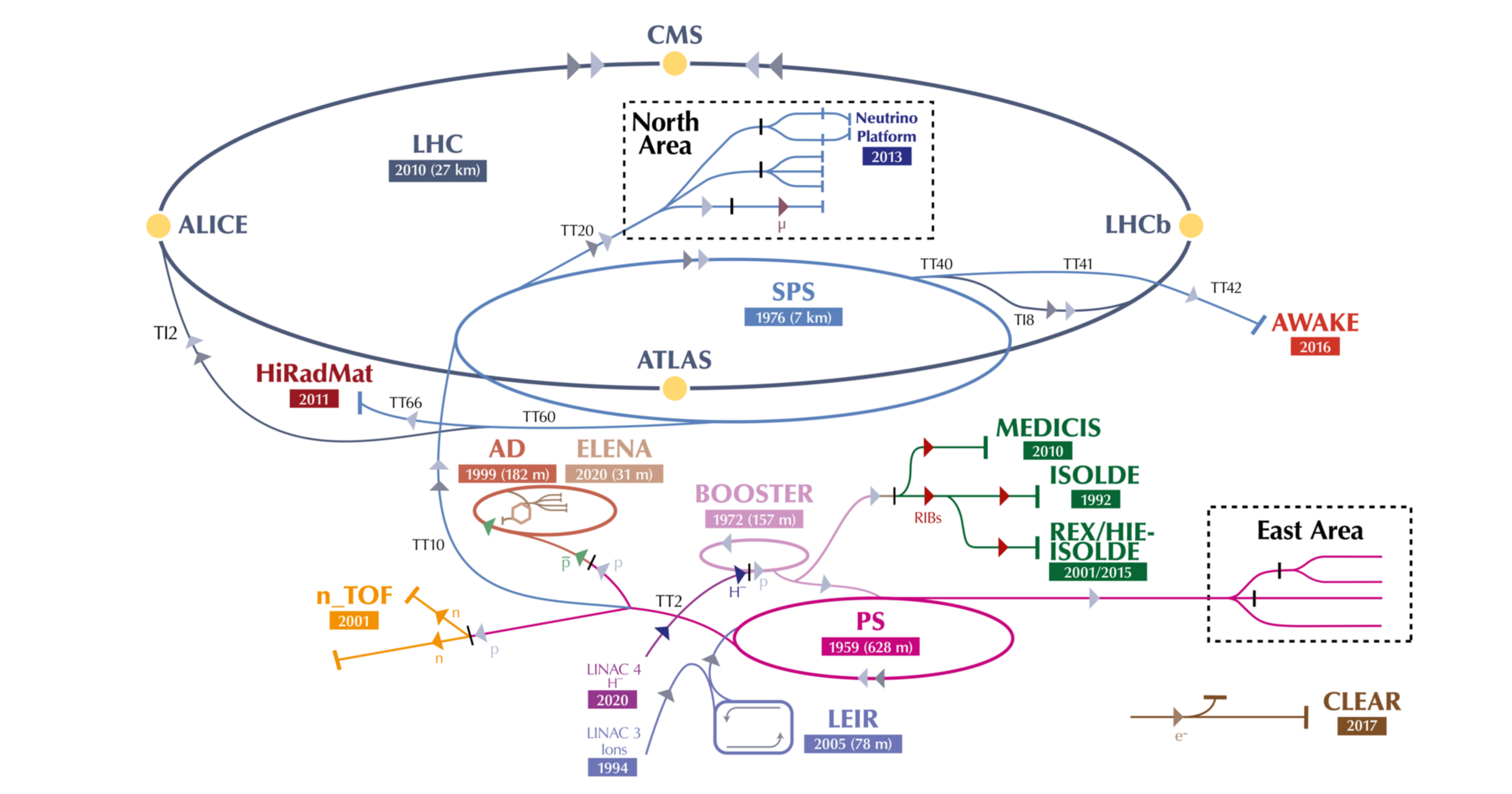
Fermi Lab

Fermi Lab

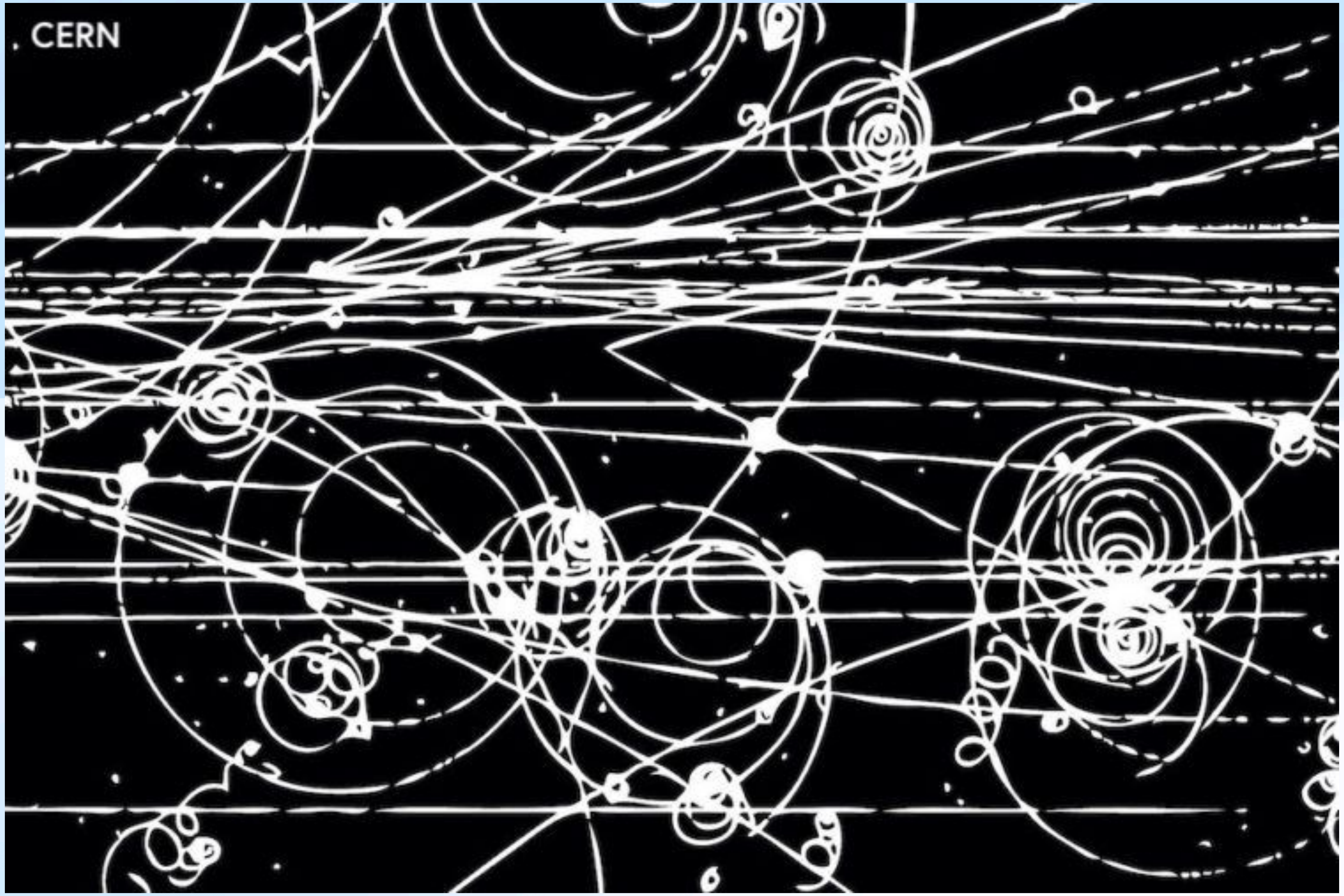


FERMILAB'S ACCELERATOR CHAIN
MAIN INJECTOR
RECYCLER
TEVATRON
DZERO
CDF
TARGET HALL
ANTIPROTON SOURCE
BOOSTER
LINAC
COCKCROFT-WALTON
PROTON
NEUTRINO
MESON
Antiproton Direction
Proton Direction

CERN


CMS
LHC
2010 (27 km)
North
Area
Neutrino
Platform
2013
μ
ALICE
LHCb
TT20
SPS
1976 (7 km)
TT40
TT41
TT42
AWAKE
2016
TI8
TI2
ATLAS
HiRadMat
2011
TT66
TT60
MEDICIS
2010
ISOLDE
1992
RIBs
REX/HIE-
ISOLDE
2001/2015
AD
1999 (182 m)
ELENA
2020 (31 m)
BOOSTER
1972 (157 m)
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.