The Quark Model

The underlying symmetry of the structure of the hadron (Mesons + Baryons) can be seen immediately if we plot particle arrangement of the various familis on a chart showing isospin component T_3 vs Strangness S.
These diagram or plot are 2-D and become 3-D once ~~charm a quark is added~~ charmness is added to it.
we will make octet (family of eight members) or eightfold way for Meson with spin-0 & spin-1

we will also make octet ~~and~~ for Baryons with spin-1/2 and decuplet (family of ten members) or tenfold way for Baryons with spin-3/2

on the same digram we also write the quark composition for ~~each~~ each members.
Green color axis in for T_3
Black color axis is for S

All these diagrams show evidence for a ~~simple~~ repeated simple structure of three particles :- u, d ~~&~~ and s (and their antiquarks $\bar{u}$, $\bar{d}$ and $\bar{s}$) quarks.

This model of quark was first suggested by Murray Gell-Mann and George Zweig.

From this model some feature of quark can be stated.

Spin = 0 mesons

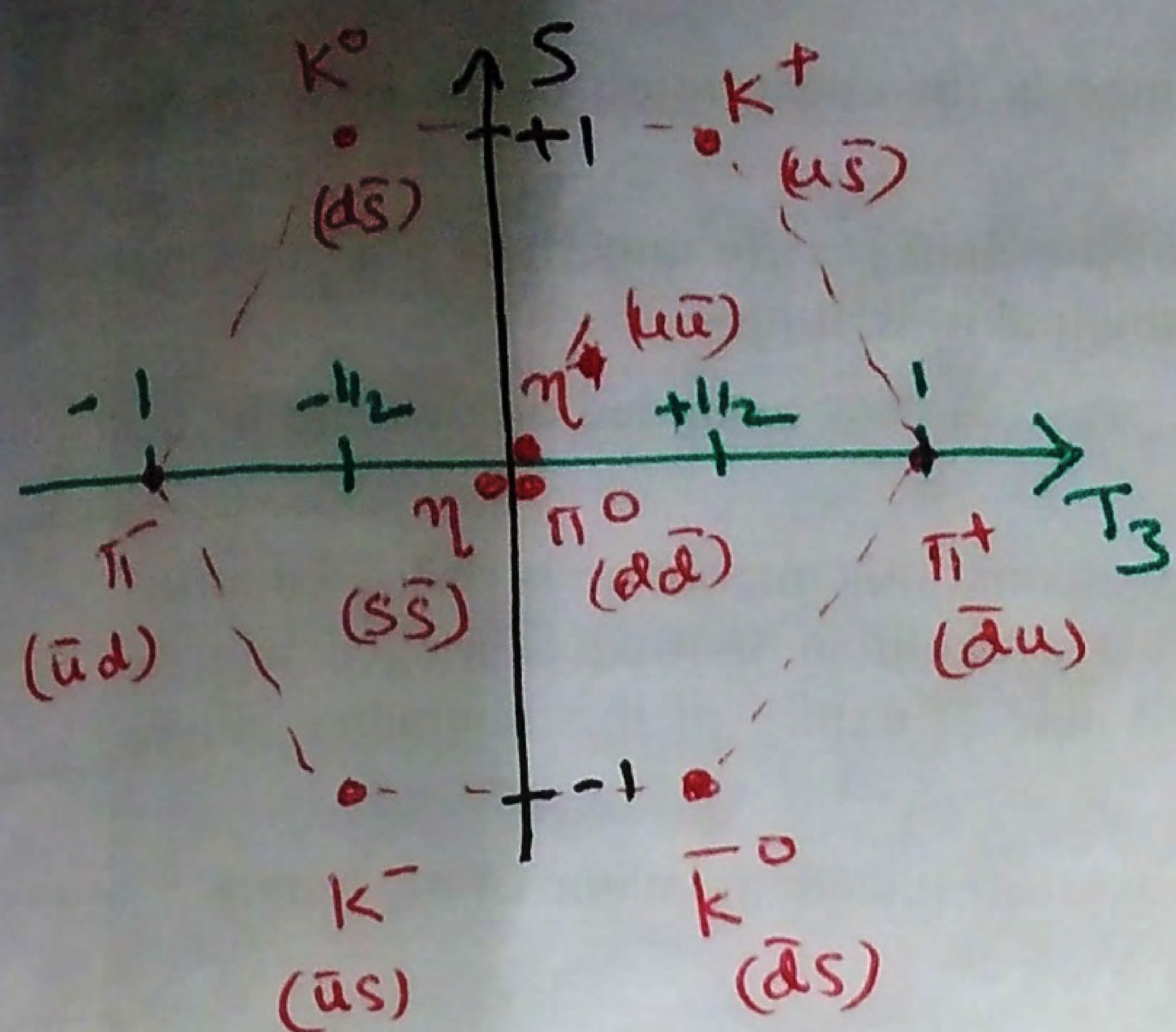


fig 1

Spin = 1 mesons

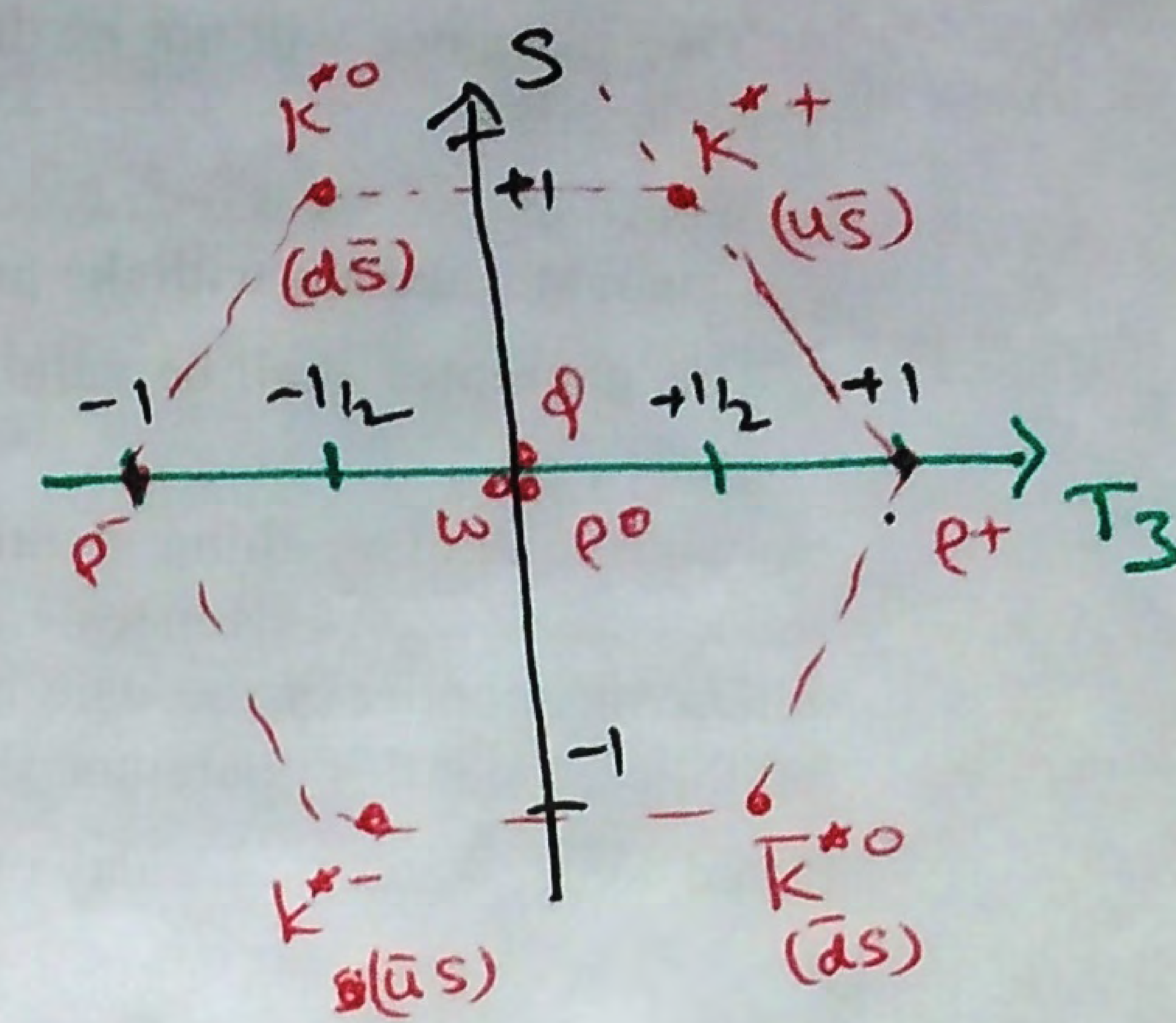


fig 2

Spin = 1/2 baryons

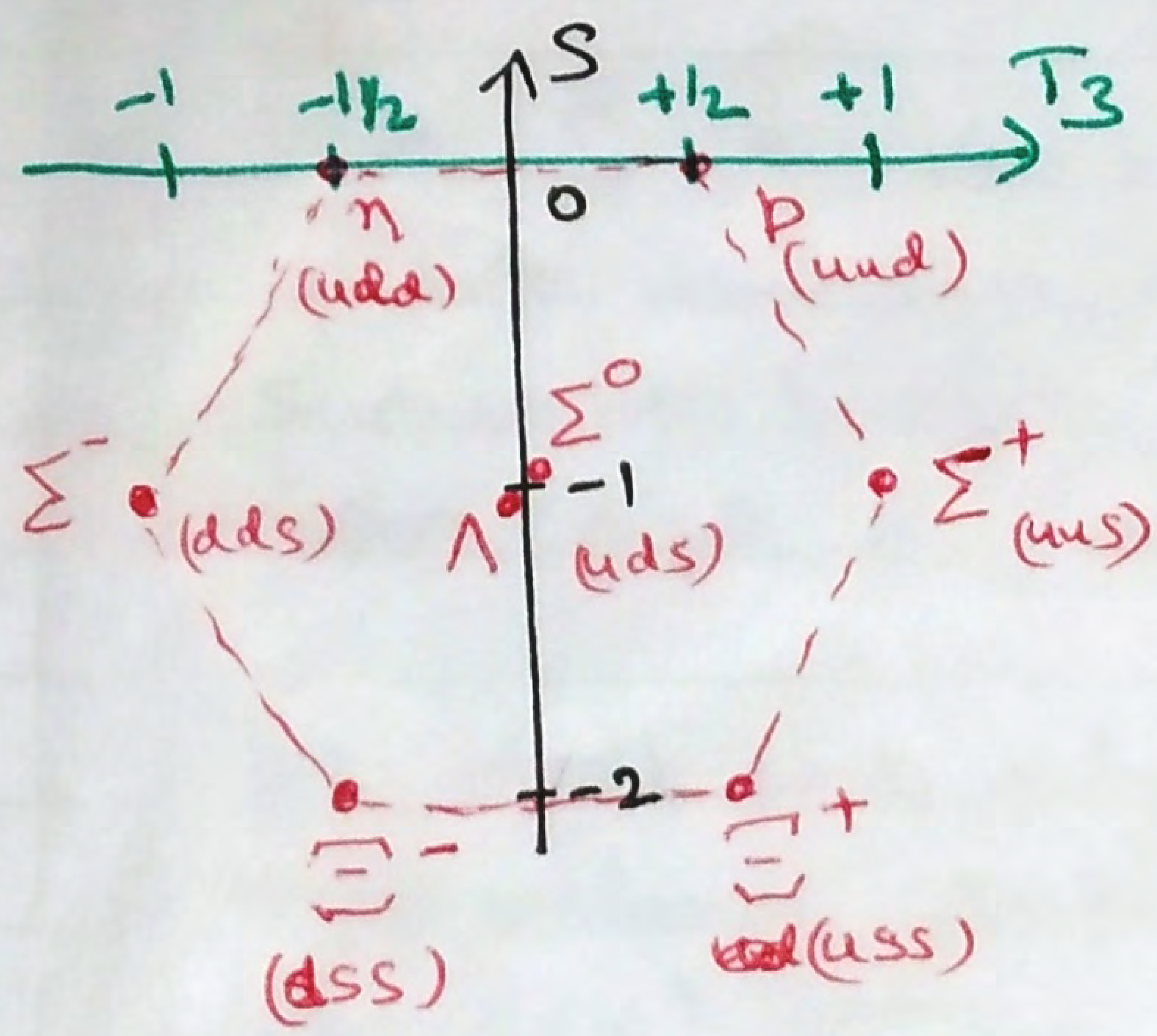


fig 3

Spin = 3/2 baryons

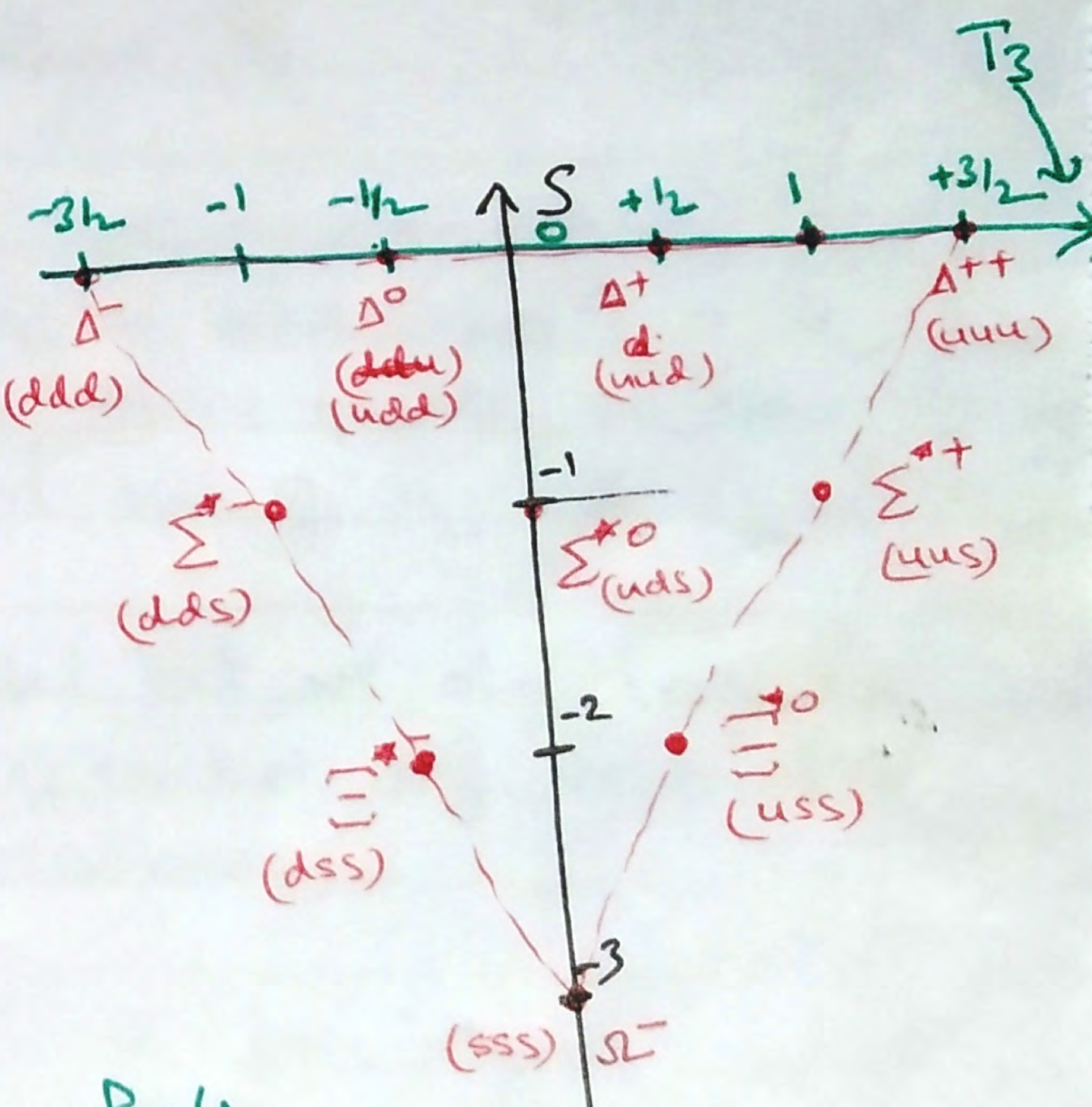
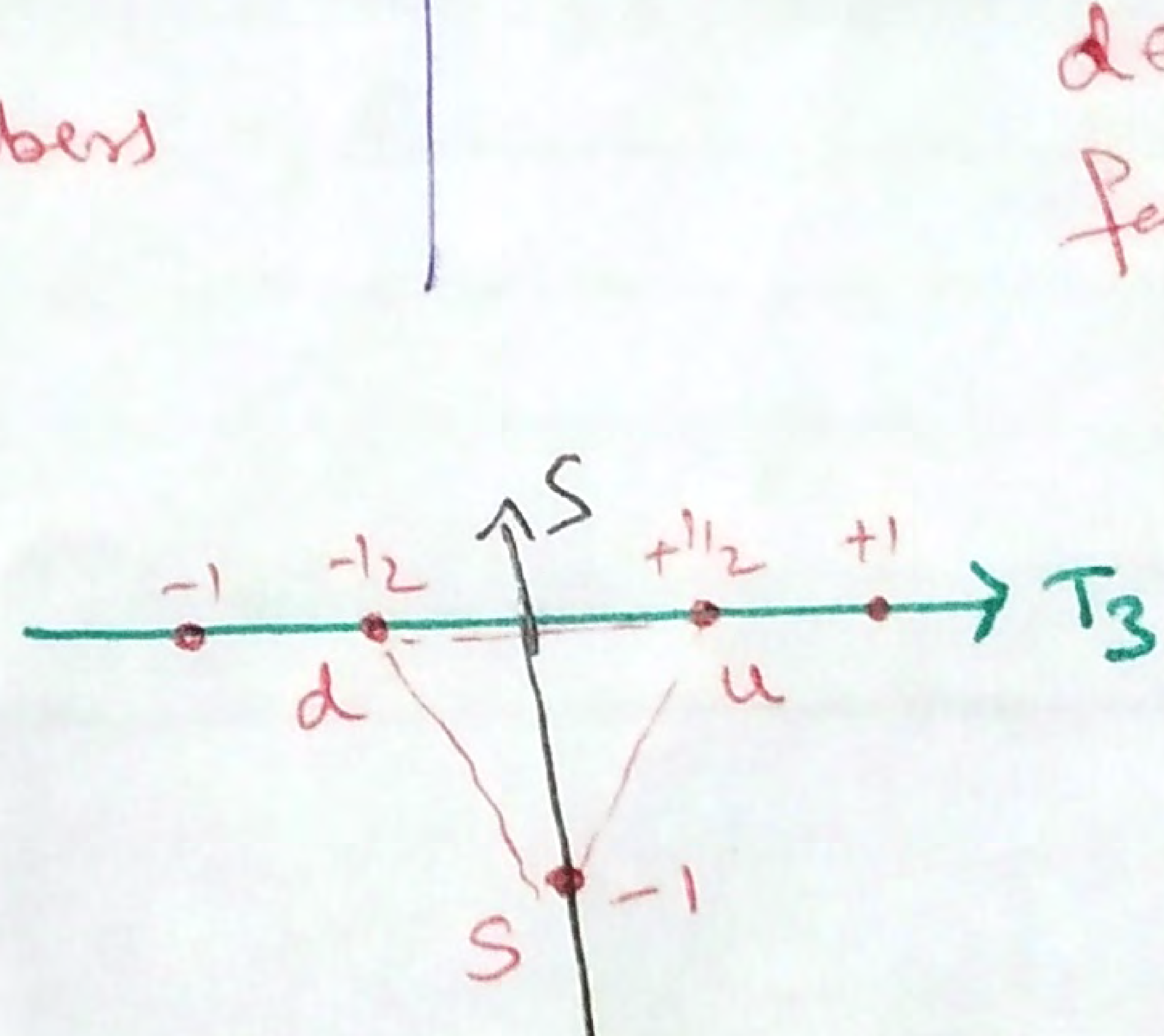


fig 4

octet
family of eight members
Eightfold way

decuplets
family of ten members
Tenfold way

(In bracket their quark composition is also written)



Ref: Page no. 719 & 720
fig no. 18.11, 18.12 & 18.13
K.S. Krane

1. Quarks have fractional electric charges.

$u = +2/3\, e$

$d = -1/3\, e$

$s = -1/3\, e$

proton = p = (uud) so total charge of p $= \frac{2}{3}+\frac{2}{3}-\frac{1}{3} \times e$

$\Rightarrow \frac{4}{3}-\frac{1}{3} \times e$

$= 3/3 = 1e$

neutron = n = (udd) so total charge of

$n = 2/3 - 1/3 - 1/3 = 0.$

2. Baryon number of quark = $1/3$

3. spin of quark = $1/2$; so mesons having two quark ~~and~~ can couple to total spin of 0 & 1. Similarly baryon having three quarks so ~~that~~ they can couple to from total spin of $1/2$ & $3/2$.

we don't have only model but we also have exp. proof. Deep inelastic scattering of nucleon by high-energy (1-100 GeV) electron or neutrinos.

outcome of exp.

1.) nucleon contains three point-like objects
2) point-like objects have spin - $1/2$
3) point-like objects have fractional charges consistent with $+2/3\, e$ & $-1/3\, e$.

{Not to be done in detail}

Colored quarks and Gluons

why quarks are Colored (new property as an additional quantum no. not any relation to ordinary colors).

why this property is introduced ?

three baryons Δ^-, Δ^{++} & Ω^- having quark configuration of ddd, uuu & sss respectively in all cases all the three quark are identical all have same set of quantum no.

spin = 1/2

~~orbital angular~~ angular momentum = 0.

~~charge same~~.

This violates the Pauli principle which is essential part for description of fermions.

in quantum mech.

$$\psi = \psi_{spin}\, \psi_{space}\, \psi_{flavor}$$

all three ψ are same and gives symmetric total wave function which violate the requirement for fermions to have antisymmetric wave function so a new property is introduce to distinguish among the identical quark of any Baryons. This property is called as color in terms of Quantum no. And there are three colors labeled as

Red (R)

Blue (B)

Green (G)

now Δ^{++} having quark as $u_R u_B u_G$

The color is selected in such a way that the Baryon itself is always colorless.

under this model the antiquark have the opposite color.
anti-Red is cyan
anti-green is magenta
anti-blue is yellow.
Combination of quark and antiquark (meson) are also colorless

Now we can write the total wave function of Baryon as quark in Baryon as

$$\psi = \psi_{spin} \psi_{space} \psi_{flavor} \psi_{color}.$$

$$\psi_{color} = \frac{1}{\sqrt{6}}\left(RGB + BRG + GBR - RBG - BGR - GRB\right)$$

and for meson, the quark wave function is

$$\psi_{color.} = \frac{1}{\sqrt{3}}\left(R\bar{R} + G\bar{G} + B\bar{B}\right)$$

The force b/t quarks can be modeled as an exchange force, mediated by the exchange of massless spin-1 particle called gluons.

{ Color is to the strong interaction b/t quarks as electric charge is to the em interaction b/t electrons. }

But photon are charge less which is field particle (exchanged b/t charged particle) in em interaction on the other hand Gluons can be colored (mostly colored) field particle.

There are nine possible gluons; $R\bar{R}$, $R\bar{B}$, $R\bar{G}$, $B\bar{R}$, $B\bar{B}$, $B\bar{G}$, $G\bar{R}$, $G\bar{B}$, $G\bar{G}$.

in which $R\bar{R}$, $G\bar{G}$, $B\bar{B}$ are coupled in 3 different ways.

$$\frac{1}{\sqrt{2}}(R\bar{R} - G\bar{G})$$

$$\frac{1}{\sqrt{6}}(R\bar{R} + G\bar{G} - 2B\bar{B})$$

$$\frac{1}{\sqrt{3}}(R\bar{R} + G\bar{G} + B\bar{B})$$

Reactions and Decays in the Quark Model.

All reactions and decays of elementary particles can be understood within the quark model, and reaction cross sections and decay lifetimes can be calculated. But following rules to be followed.

1) Strong interaction cannot change the flavors of quarks; only rearrangements of quarks among particles can occur.

2) Quark-antiquark pairs can be created and annihilated, in exact analogy to positron-electron creation and annihilation with photons.

3) Weak interaction can change the quark flavor through the emission or absorption of a $W^{\pm}$ weak boson

$u \rightarrow d + W^+$ $\qquad$ $\bar{u} \rightarrow \bar{d} + W^-$

$s \rightarrow u + W^-$ $\qquad$ $\bar{s} \rightarrow \bar{u} + W^+$

Neutral weak flavor-changing processes are forbidden

example $s \rightarrow d + Z^0$ forbidden

$$Z^0 \rightarrow u + \bar{u}$$
or
$$\rightarrow d + \bar{d}$$
or
$$\rightarrow s + \bar{s}$$
} are possible.

Examples.

1) $$\pi^+ + p \longrightarrow \pi^0 + \Delta^{++}$$

(no lepton) Lepton no. is conserved. $0 = 0$

Baryon no. is conserved $1 = 1$

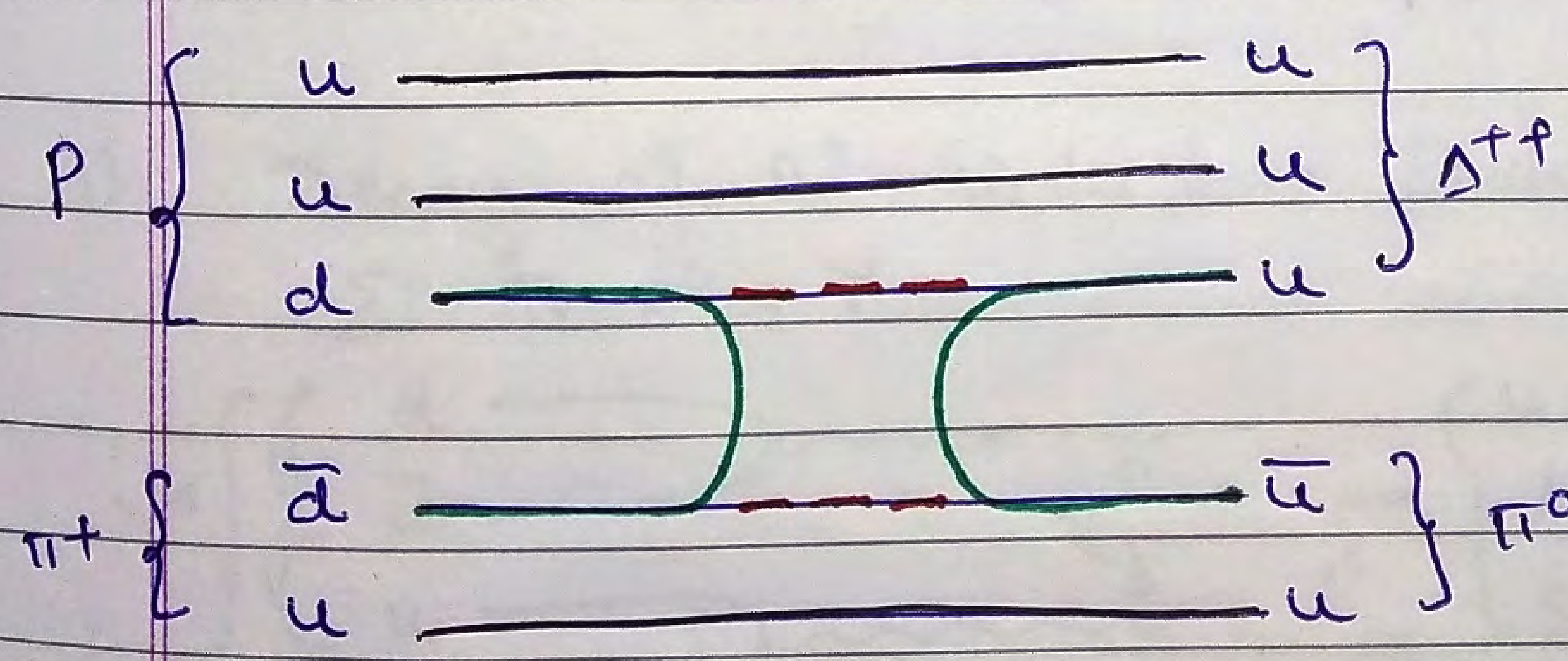
Isospin I is conserved $\pm 1 \pm \frac{1}{2} = \pm 1 \pm 3/_2$

$\neq$

may be a weak interaction.

Strangeness is also conserved. $0 = 0$

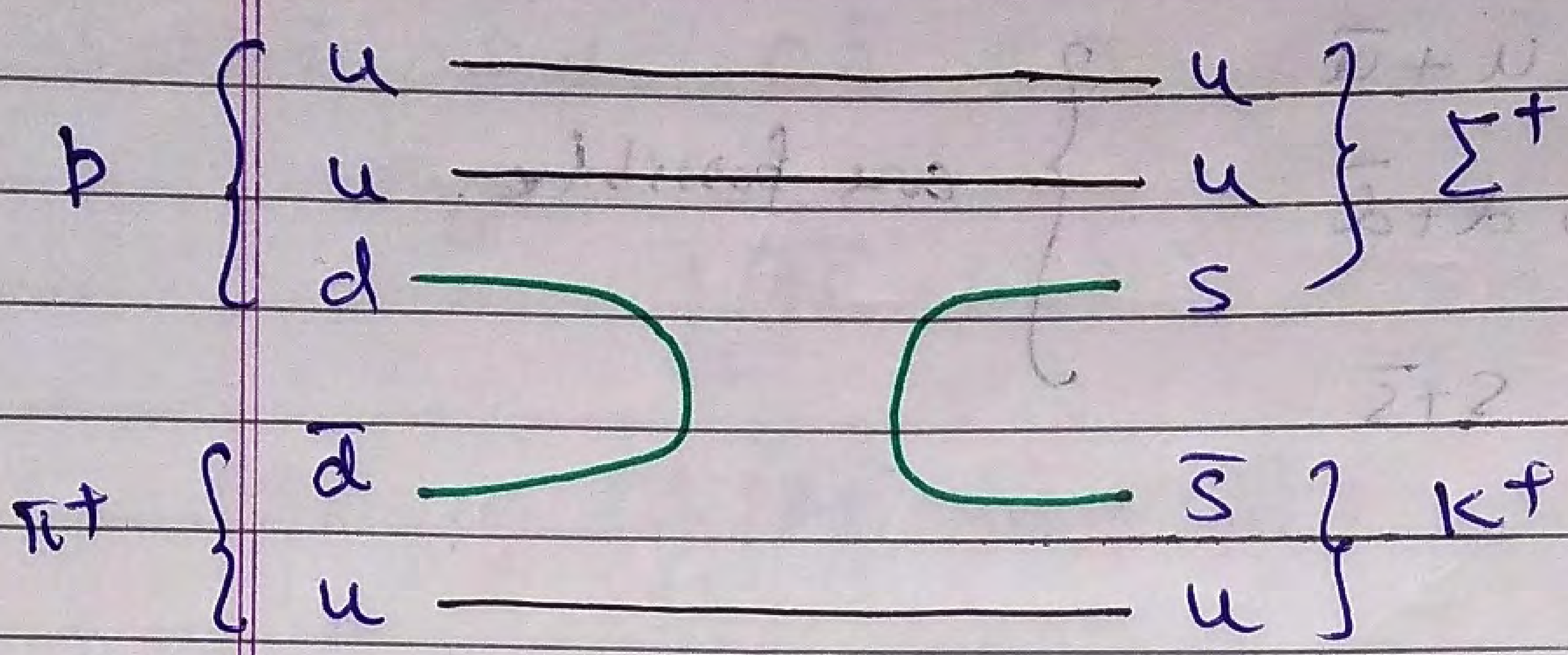
As per quark model.



annihilation of a $d\bar{d}$ pair and a creation of $u\bar{u}$ pair.

The created pair can be $s\bar{s}$ and the product will change.

$$\pi^+ + p \longrightarrow \Sigma^+ + K^+$$



we can imagine as if

$$d+\bar{d} \longrightarrow \text{gluon} \longrightarrow u+\bar{u}$$

or

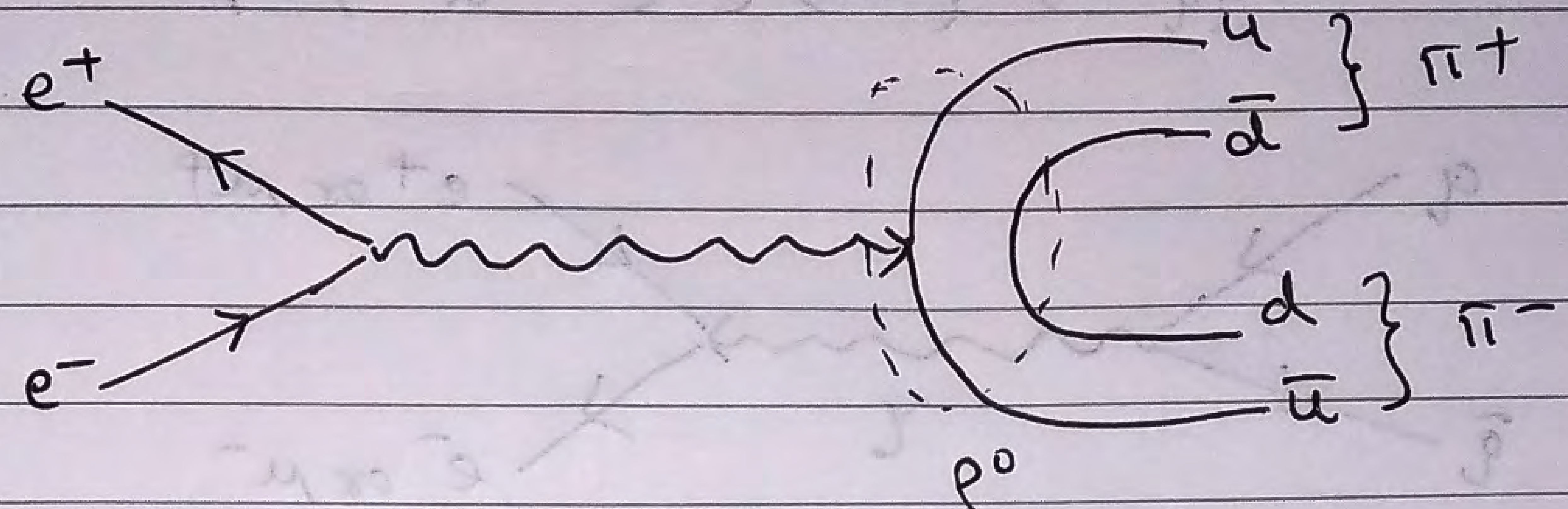
$$\longrightarrow s+\bar{s}$$

But the process is not so simple; not only one gluon but several gluons are continually being exchanged among the component quarks with diffrent color.

For ref. you can see fig 18.19 showing colors of quarks and exchanged gluons for reaction.

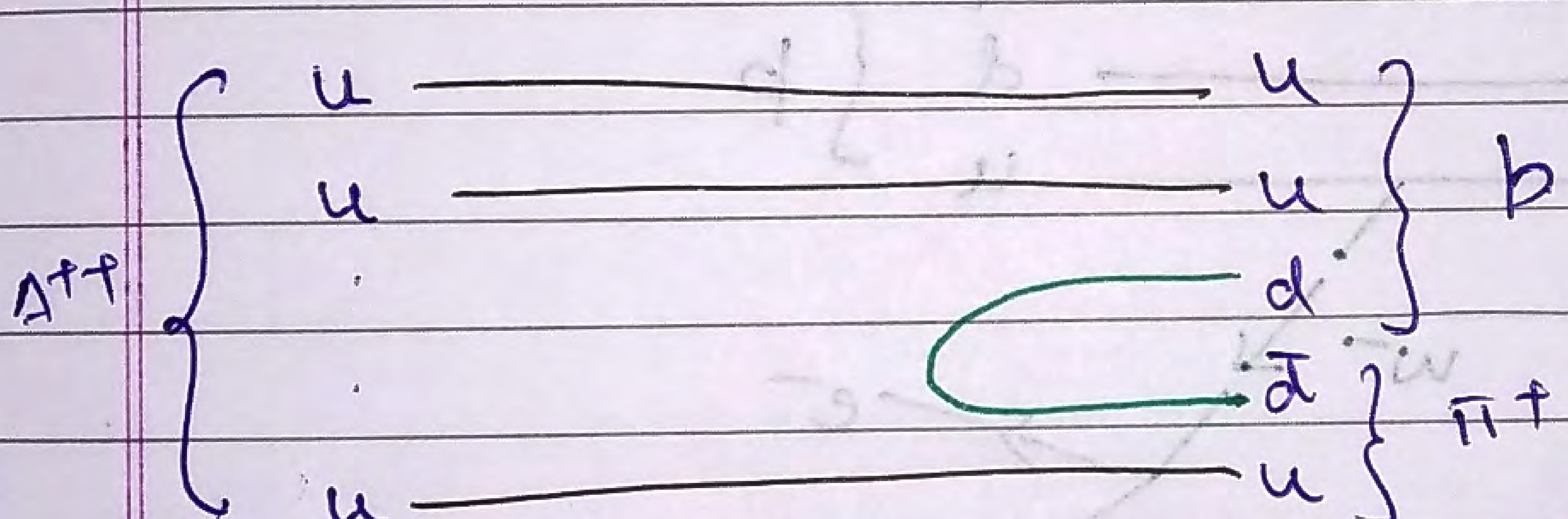
$$\pi^{+}+p \longrightarrow \Sigma^{+}+K^{+}$$

2) production of hadron in $e^+ e^-$ collisions.

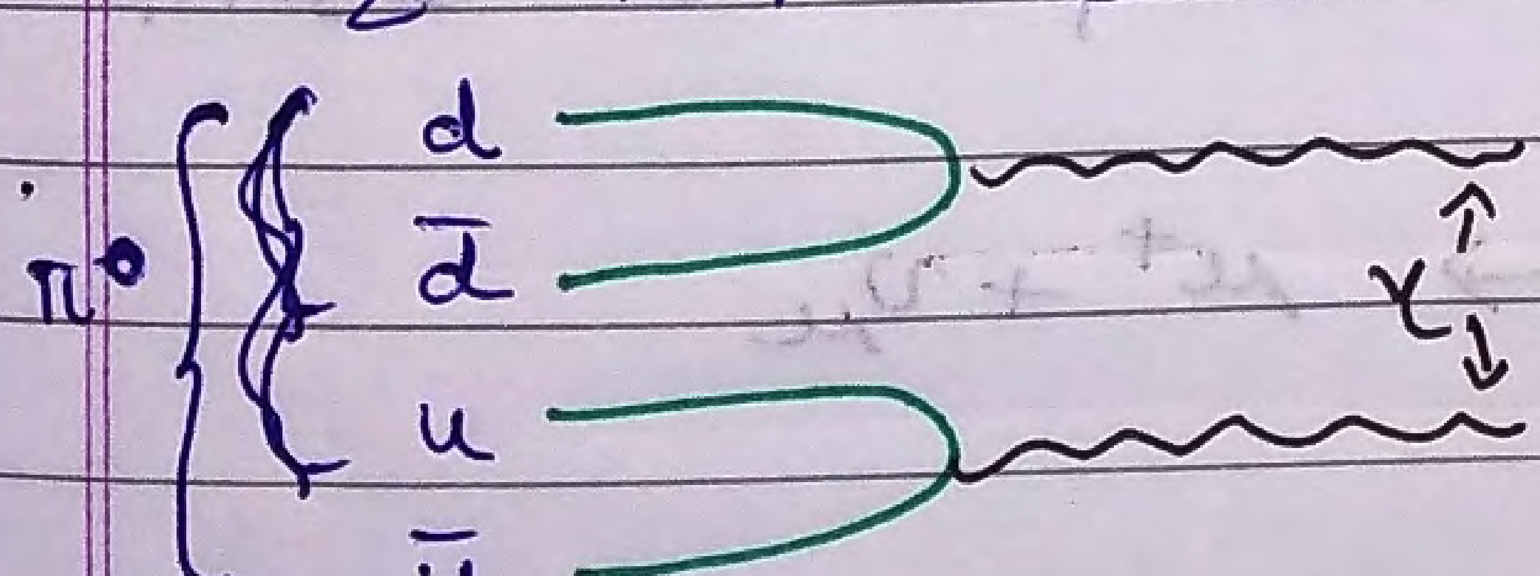


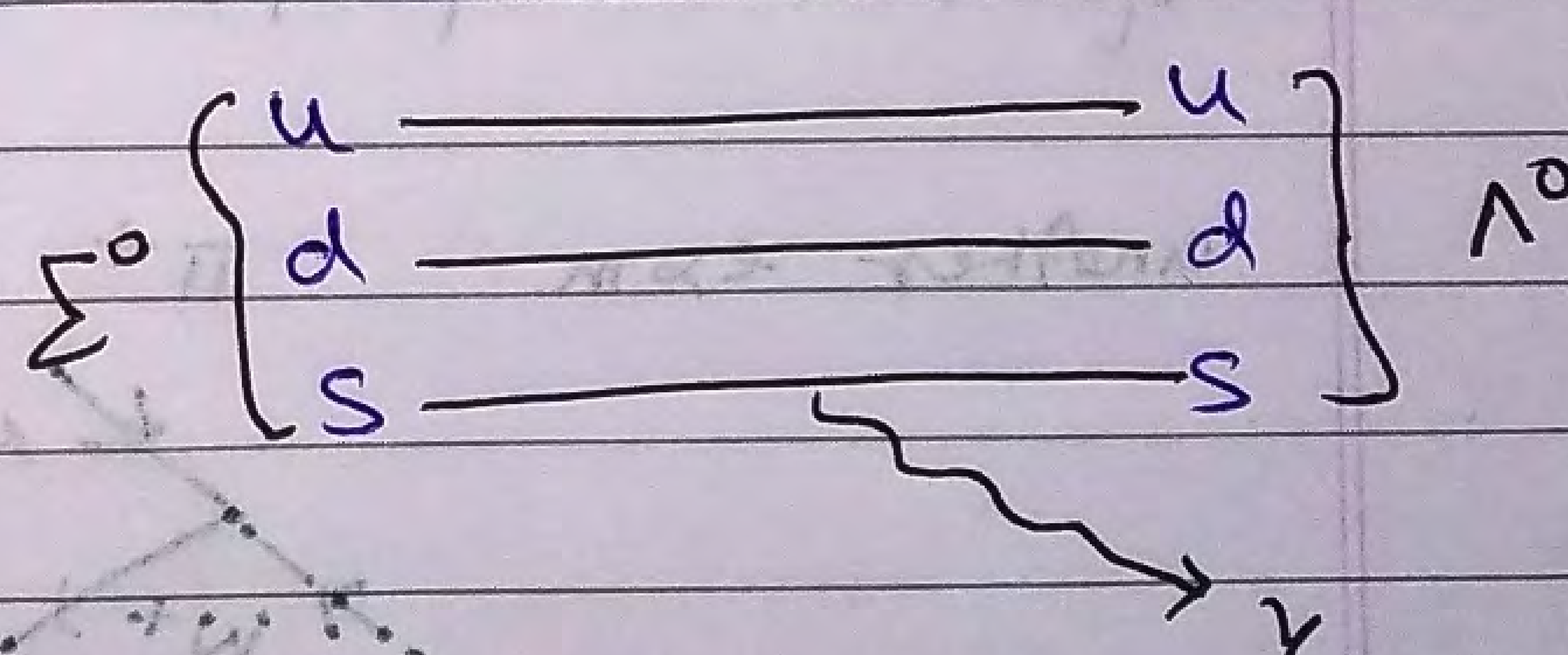
ρ^0 strongly decay to $\pi^+ + \pi^-$

3) $\Delta^{++} \longrightarrow p + \pi^+$



4) Decay of π^0 into two photons and decay of Σ^0 to $\Lambda^0 + \gamma$



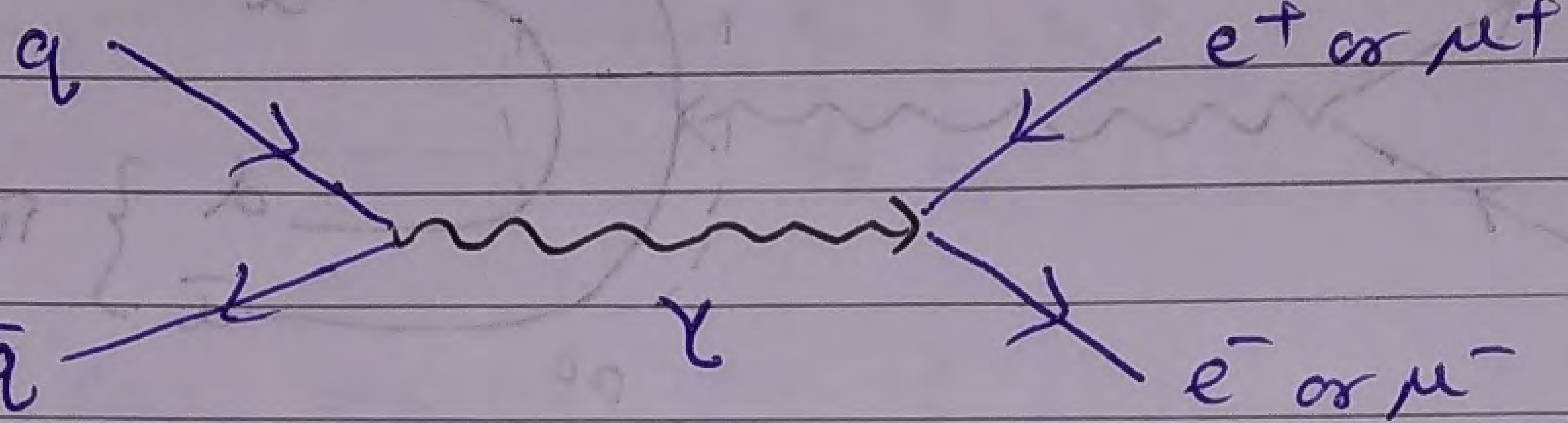


$\pi^0 \longrightarrow \gamma + \gamma$

$\Sigma^0 \longrightarrow \Lambda^0 + \gamma$

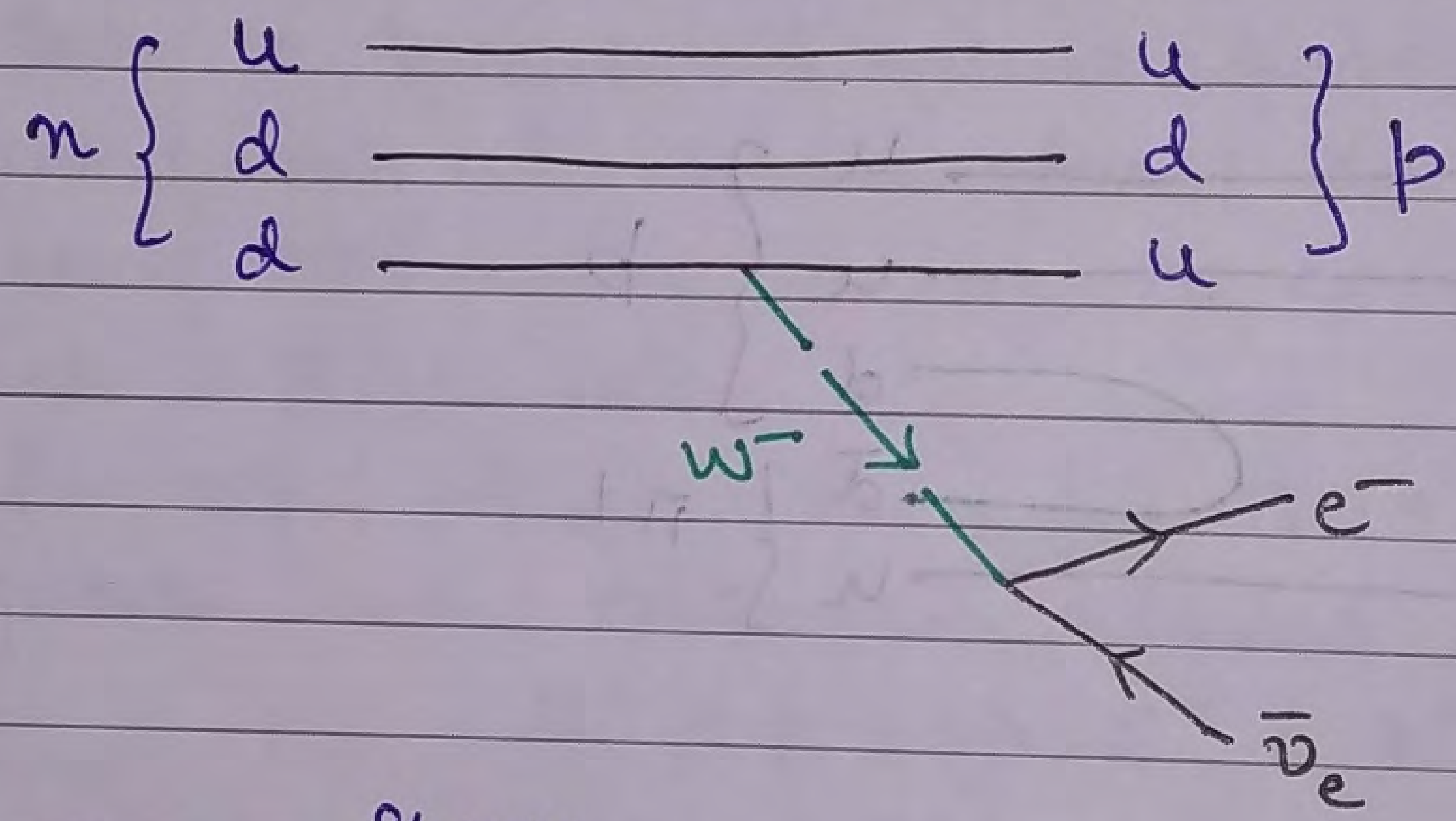
5) leptonic decays of the mesons can occur electro-magnetically

$$q\bar{q} \rightarrow \gamma \rightarrow e^+e^- \text{ or } \mu^+\mu^-$$



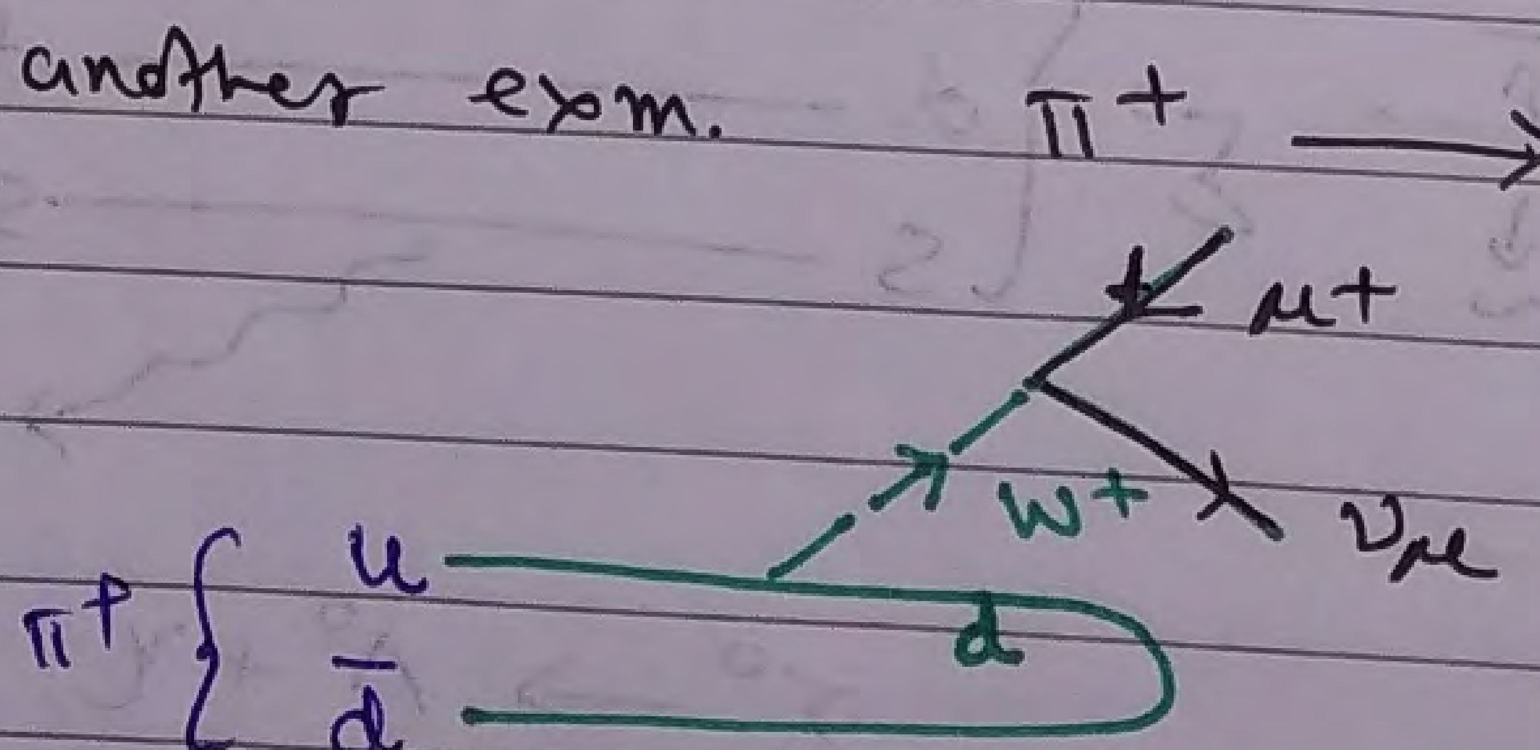
6) weak decays of quarks can change quark flavors

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



one d flavor quark in neutron changes to u flavor quark in proton by emitting a W^- boson.

another exm. $\pi^+ \longrightarrow \mu^+ + \nu_\mu$



$$u \rightarrow W^+ + d \rightarrow d + \bar{d} \rightarrow \mu^+ + \nu_\mu$$