[noncommutative]

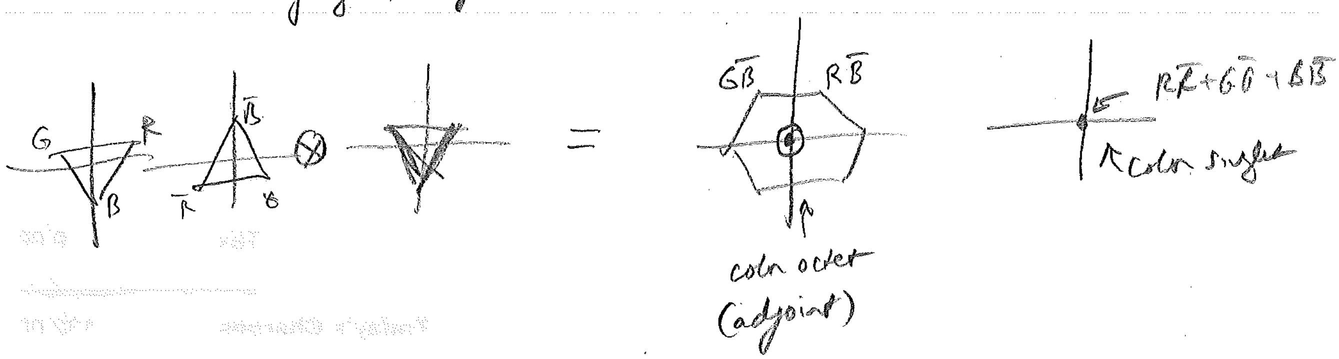
## Nonabelian gauge theories SU(N)

Contains a set of $N^2-1$ spin-1 gauge bosons belonging to the <u>adjoint</u> rep of SU(N)

adjoint rep is contained in the product of fund. ⊗ $\overline{\text{fund}}$

$$\underset{\sim}{N} \otimes \underset{\sim}{\overline{N}} = \underset{\text{adjoint}}{(N^2-1)} \oplus \underset{\text{singlet}}{1}$$

e.g. $SU(3)_c$ gauge theory $\quad \underset{\sim}{3} = \begin{pmatrix} R \\ G \\ B \end{pmatrix} \quad \underset{\sim}{\overline{3}} = \begin{pmatrix} \overline{R} \\ \overline{G} \\ \overline{B} \end{pmatrix}$




8 gauge bosons = gluons

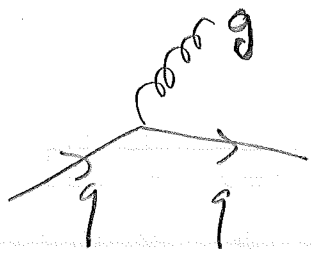
Since gluons do <u>not</u> belong to a color singlet, they are not observable in isolation (confinement)

~~Because~~ Gluons only interact w/ objects w/ color

Quantum chromodynamics (QCD)
[Politzer Gross Wilczek 1973]

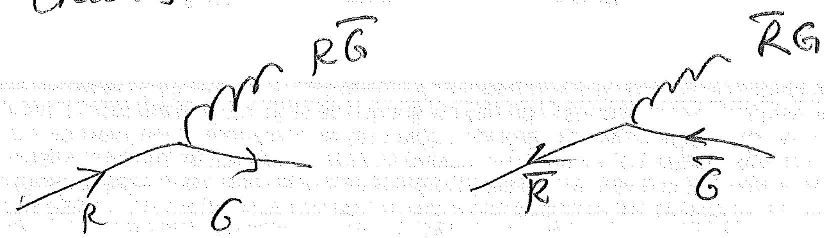
= $SU(3)_c$ gauge theory { w/ 8 gluons (in the adjoint rep) <u>plus</u> quarks (in the fundamental rep)

<u>QCD vertex</u>




Color is conserved at each vertex;
gluons allow quarks to change color

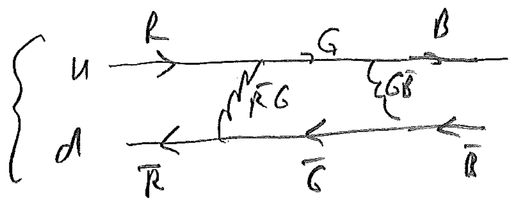
[use colored chalk]

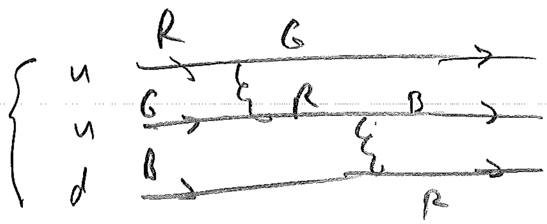


Recall only hadrons that are color-singlets (i.e. 1 dim'l reps of $SU(3)_c$) are observable in isolation

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

baryons: $\frac{1}{\sqrt{6}}(RGB \pm \text{perms})$

$\pi^+$ 


p 

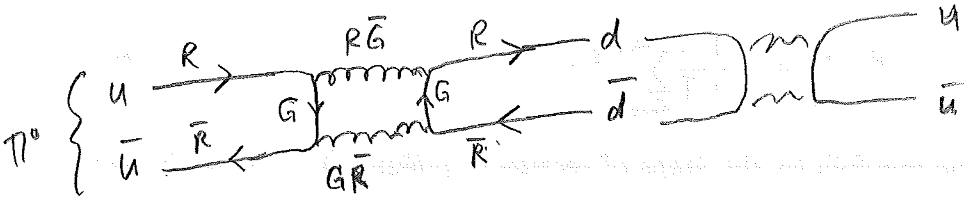

gluons do not allow quarks to change flavor

so (e.g.) strangeness is conserved in strong interactions

$\pi^+ = u\bar{d}$

$\pi^- = d\bar{u}$

$\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$

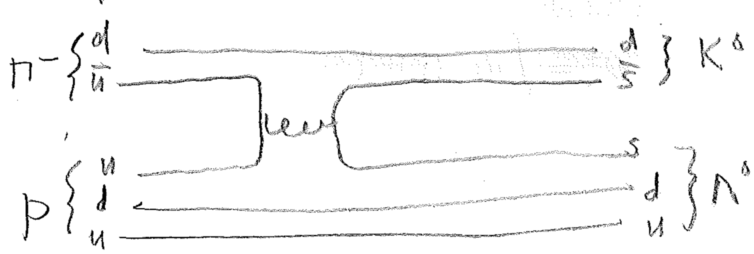



Strong interaction decay + scattering involve exchange and/or creation of quarks

$\pi^+\pi^- \to \pi^0\pi^0$


$\Delta^{++} \to p\pi^+$

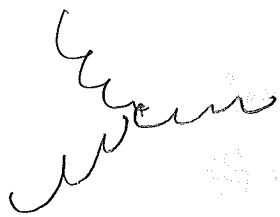

Associated production: $\pi^- p \to \Lambda^0 K^0 \Rightarrow$ Strangeness conserved




($s, \bar{s}$ created in pairs)

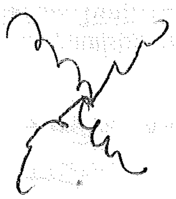
REDO

gluons have color + can couple to gluons



$8 \otimes 8 = 8 \oplus \ldots$

[doesn't happen w/ photons]



QED is linear, QCD is nonlinear
(superposition)

QCD-5

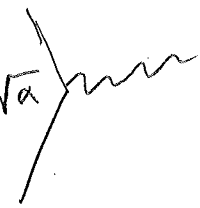
$\alpha = \frac{e^2}{4\pi\epsilon_0 \hbar c} \approx \frac{1}{137}$

REDO

REDO

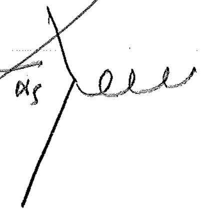
QED

$e \sim \sqrt{\alpha}$



QCD

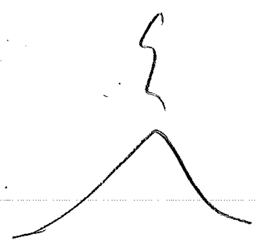
$\sqrt{\alpha_s}$

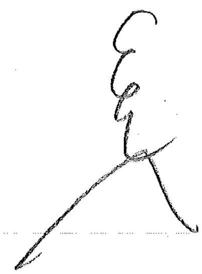


$\alpha \approx \frac{1}{137} \Rightarrow$ weak

$\alpha_s \approx 1 - 10$

[Halzen + Martin]

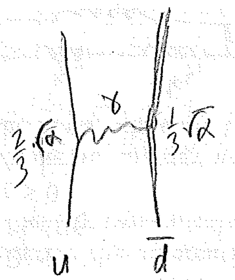




## 2 consequences

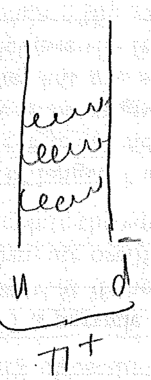
① force between quarks much stronger

[therefore force between 2 qks by gluon exchange is much larger than Coulomb force]




$\frac{2}{3}\sqrt{\alpha}$, $\frac{1}{3}\sqrt{\alpha}$ $\Rightarrow \frac{\frac{2}{9}\alpha}{r^2}$ (repulsive)

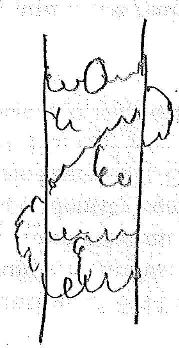
~~Color introduced as new quantum # to solve Fermion statistics; but it's also a source of gluons of new force~~




$\Rightarrow$ strong attraction

② higher order diagrams just as important as (or more so) ~~lowest order~~ tree diagrams $\Rightarrow \infty$ # of diagrams

impossible to calculate



→ unlike hydrogen, no one has computed binding of u & d̄ to give π⁺

→ It is believed, but no one has proved, that ~~the force~~ quarks can never be isolated due to exchange of gluons

(Confinement hypothesis)

→ 2 issues

– Experimental: no qks observed

→ Does QCD *predict* confinement?

→ ∴ Does QCD describe reality?

[Griffiths 2.3, fig 2.3] QCD-7

REDO

one model suggests that gluon exchange leads to $F = F_0$ (const) (rather than $\frac{1}{r^2}$)

so $U = F_0 r$

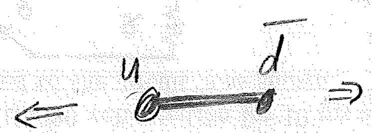
~~so that pulling qks apart~~

as if qks were connected w/ a string w/ constant tension

experiment $\Rightarrow F_0 \approx 16$ tons $= 16 \frac{(2000 \frac{lbs}{ton})}{(2.2 \frac{lbs}{kg})} (10 \frac{m}{s^2}) = 1.5E5\ N$

$= \frac{(1.5E5)\ J/m}{(1.6E{-13}\ J/MeV)} = E18\ \frac{MeV}{m}$

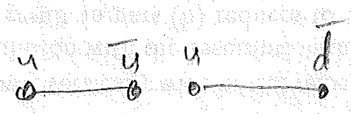
$= 1000\ \frac{MeV}{fm}$





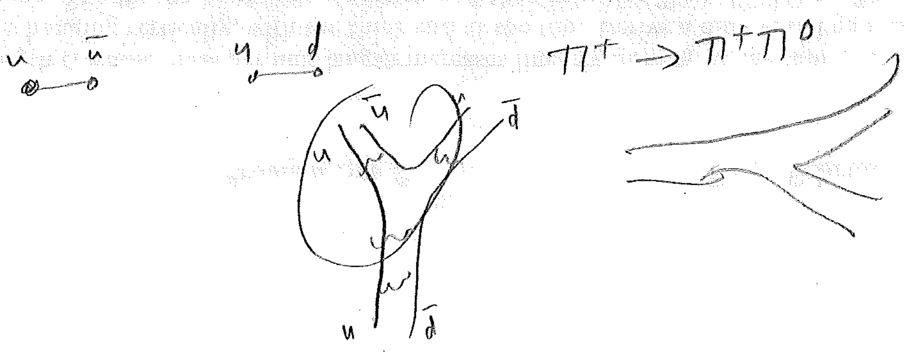
extend by fract of fm $\Rightarrow$ require 10's of MeV

$\rightarrow$ create $u\bar{u}$ pair




string snaps

$\pi^+ \rightarrow \pi^+ \pi^0$



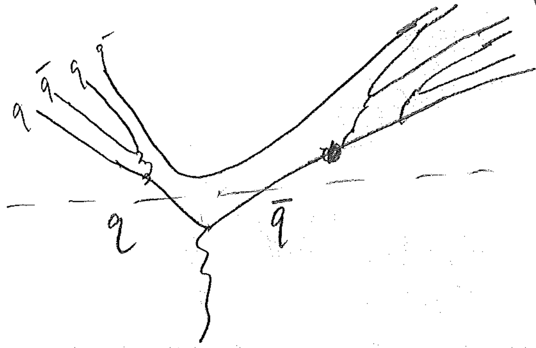
QCD 8

Left to right

REDO

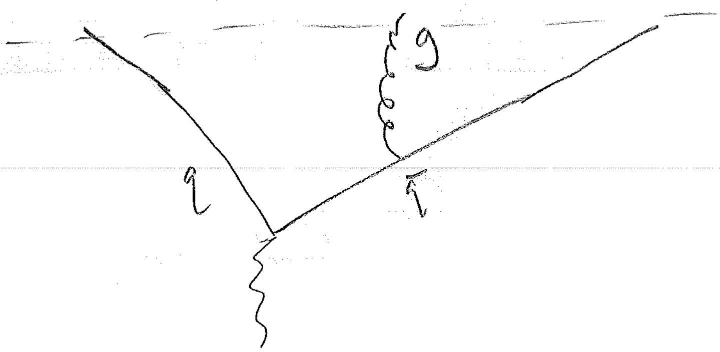
redo

Hadronization



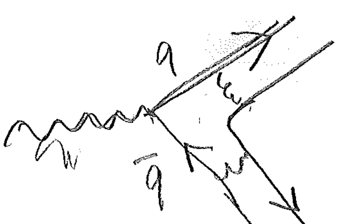

⇒ 2-jets

4 picture




⇒ 3-jets

Cpenkus 8.28



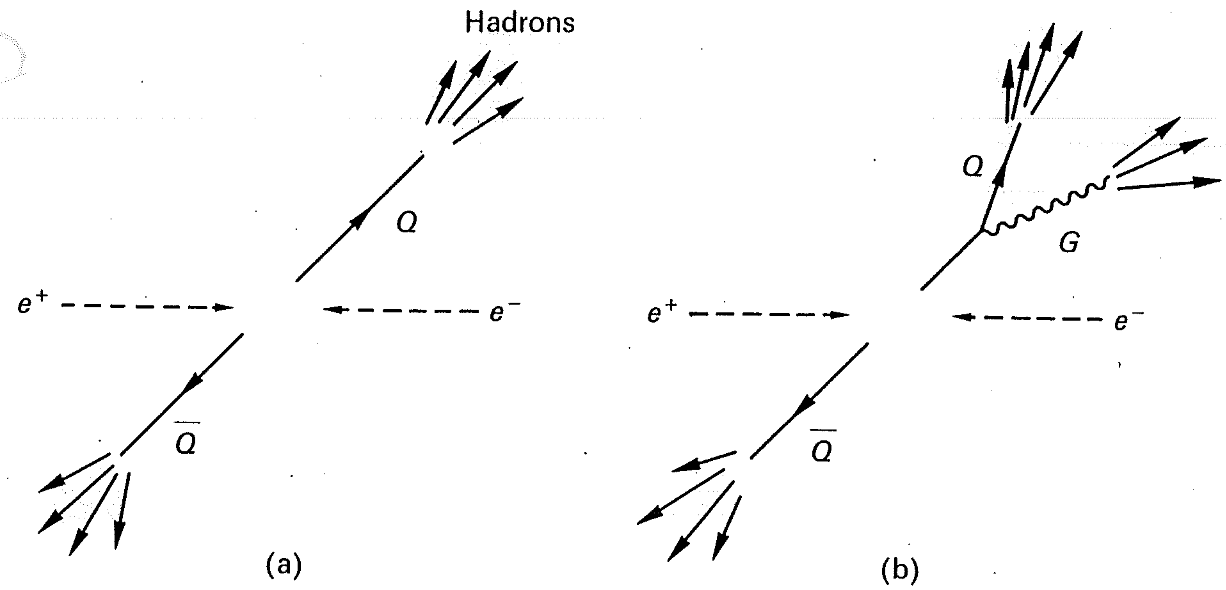




**Fig. 8.27**

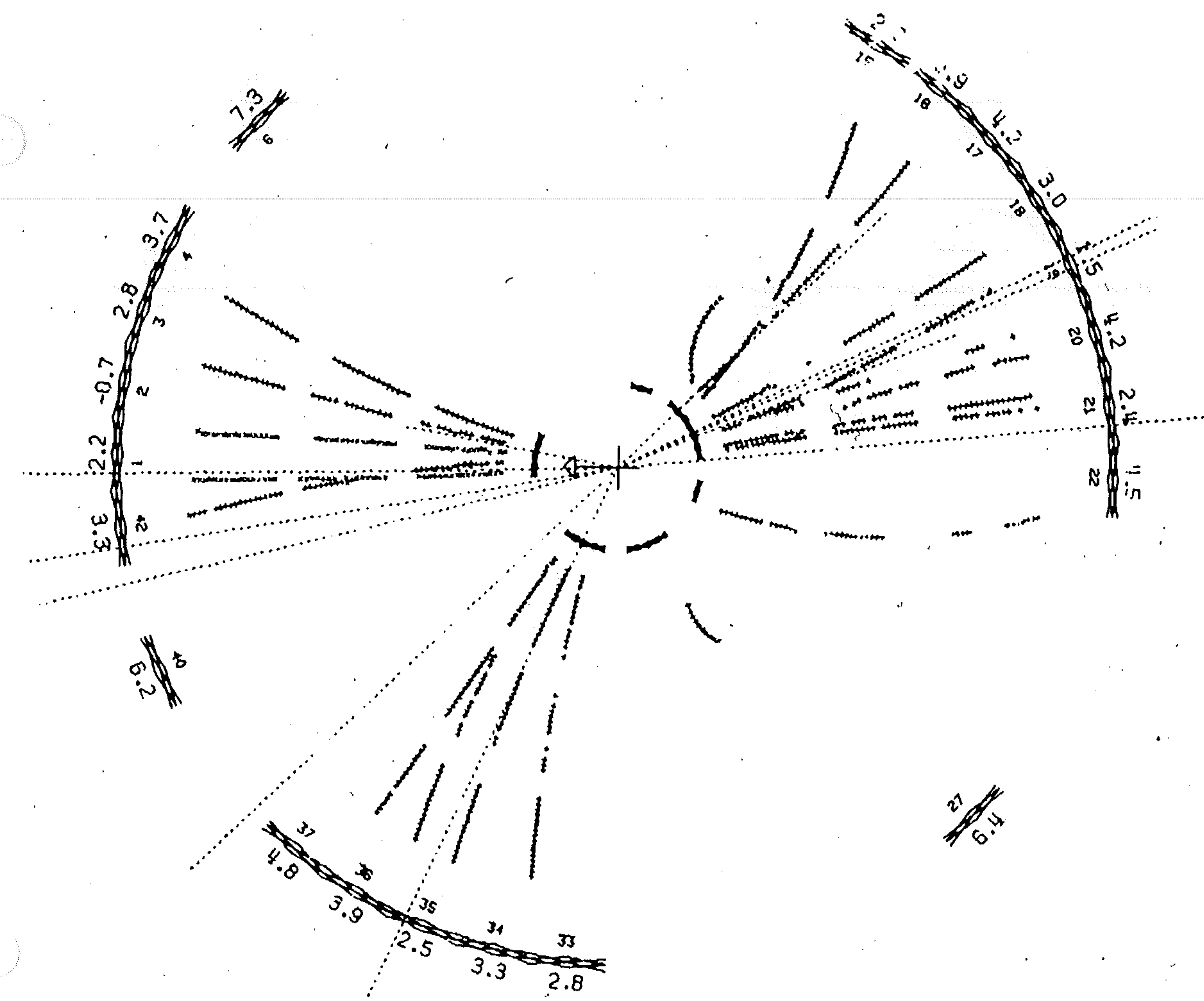


**Fig. 8.28** Example of a three-jet event observed in the JADE detector at the PETRA $e^+e^-$ collider

Perkins

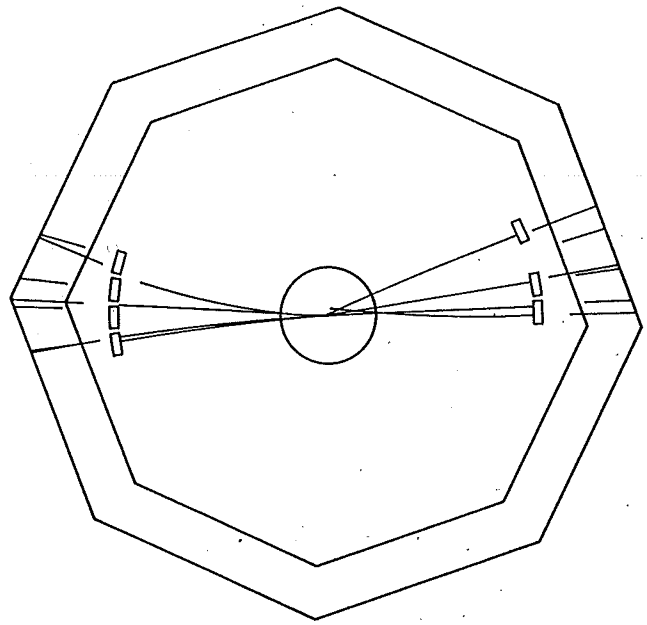


**Figure 8.1** A typical two-jet event. (Courtesy J. Dorfan, SLAC.)

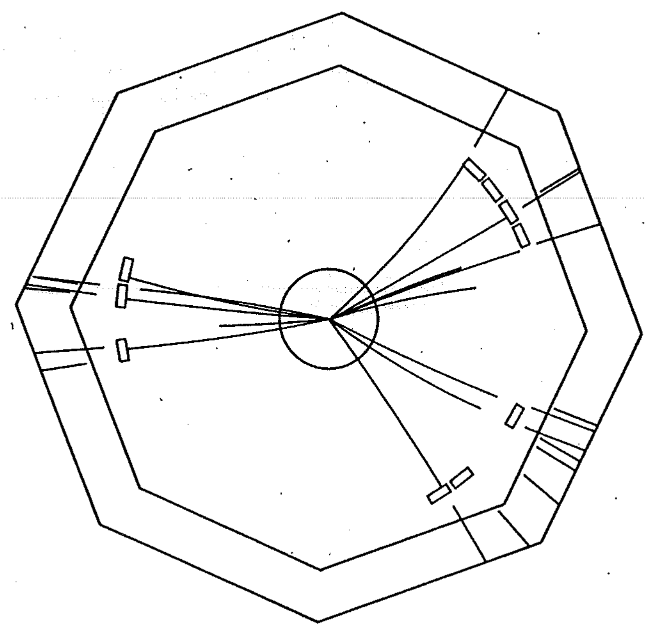


**Figure 8.2** A three-jet event. (Courtesy J. Dorfan, SLAC.)

Griffiths

HW problem

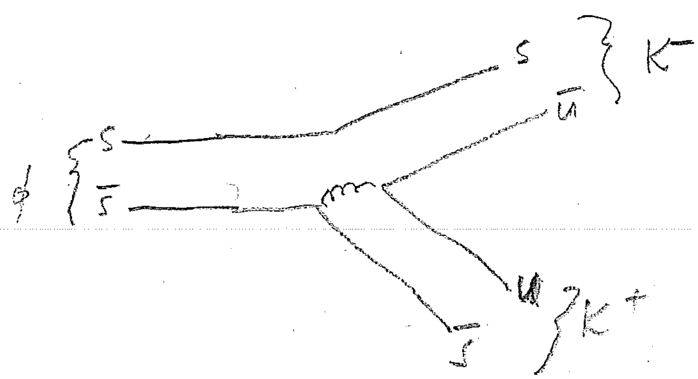
$\boxed{\phi(1020) = s\bar{s}}$

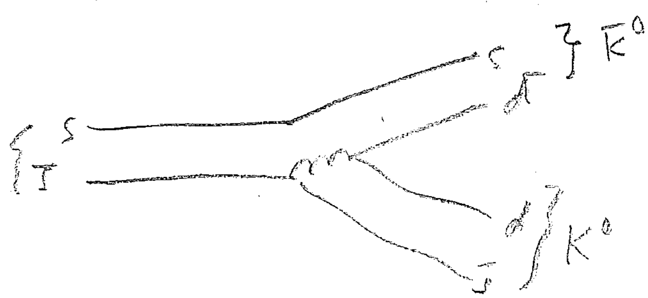
$m = 1020$ MeV

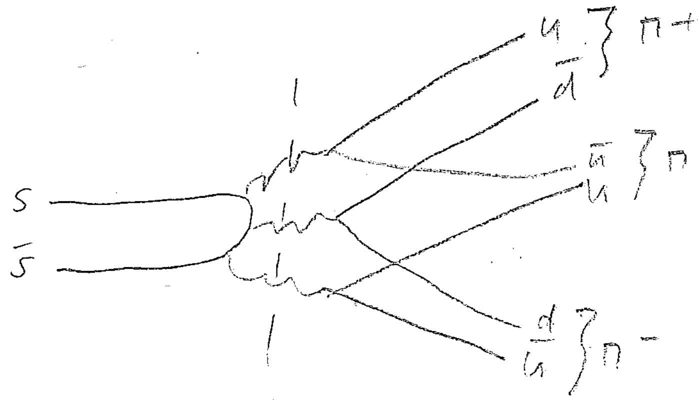
$\tau = 1.5 \times 10^{-22}$ s (strong decay)

| | BR | Q |
|---|---|---|
| $\phi \rightarrow K^+K^-$ | 49% | 30 MeV |
| $\rightarrow K^0_L K^0_S$ | 34% | |
| $\rightarrow \pi^+\pi^0\pi^-$ | 15% | 600 MeV |

$\phi \rightarrow \pi^+\pi^-$ violates G parity




(OZI suppressed)