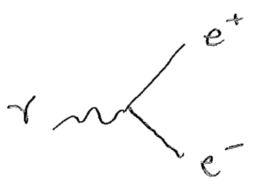
[What holds the quarks together?
A new force, called the color-force
based on the nonabelian gauge group SU(3)]

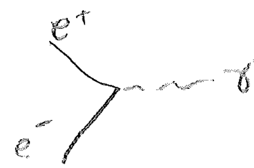
[Let's review EM force from point of view of Feynman diagrams]

QED vertex

[or any electrically charged particle]

Also





- Vertex carries factor of e
- Strength of force proportional to $\frac{e^2}{4\pi} \sim \frac{1}{137} \ll 1$ EM force is weak.

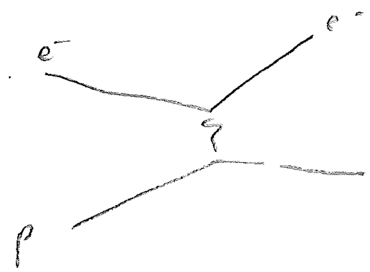
$$\frac{e^2}{4\pi\epsilon_0\hbar c}$$

Bound states:

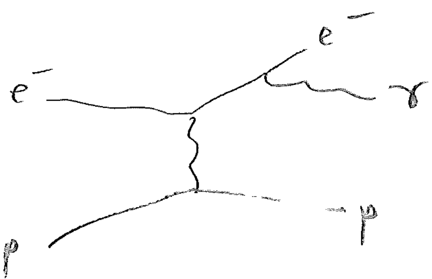
virtual photons bind e^- & p into an electrically neutral hydrogen atom

[Is this the first time talk about bound state — [illegible]]

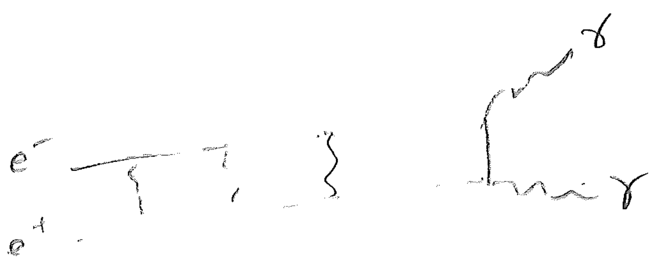
Elastic scattering: $e^- p \to e^- p$



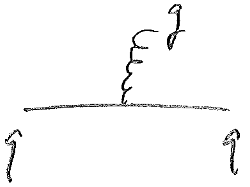
Inelastic scattering (bremsstrahlung): $e^- p \to e^- p \gamma$

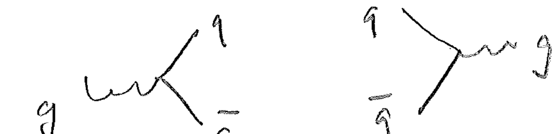


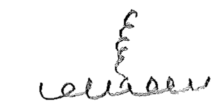
Positron annihilation: $e^- e^+ \longrightarrow \gamma\gamma$



color force

QCD vertex  [any particle w/ color charge]

Also 



gluon self-interaction
(because gluons have color too)

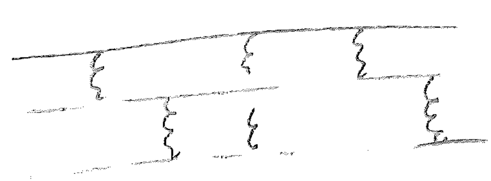
Vertex carries factor of g_s = strong coupling constant

strength $\alpha_s = \frac{g_s^2}{4\pi} \sim 1$, so gluon emission much more likely & force is very strong

[F.d. w/ many gluons are just as important.
Much harder to compute amplitudes but can use F.d. to indicate possibilities]

Bound states:

$\pi^+ = \begin{cases} u \\ \bar d \end{cases}$ 

$p = \begin{cases} u \\ u \\ d \end{cases}$ 

[many gluon exchanges so we will generally suppress them & assume they are there]

[Why 3 qks + not 2 or 4 in baryon?]

Baryons consist of 3 quarks because color force is described by a nonabelian gauge group SU(3)

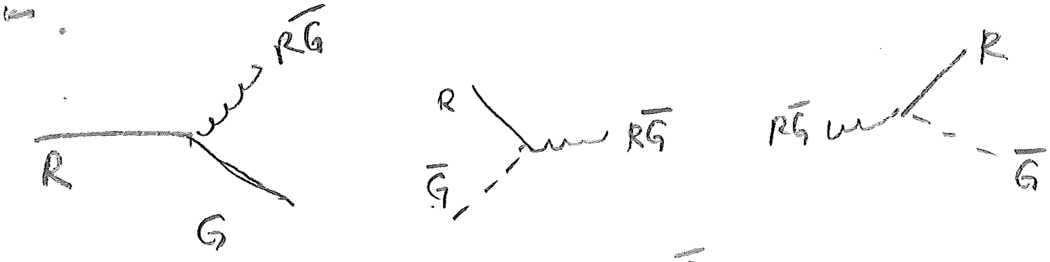
[Not GellMann's $SU(3)_F$ but $SU(3)_C$]

∃ 3 different types of color charge carried by qks, called R, G, B

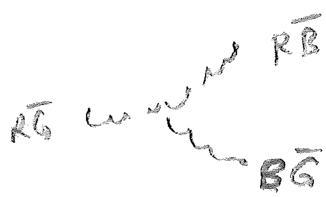
Antiquarks carry anticolor $\bar{R}, \bar{G}, \bar{B}$

Gluons carry both a color & an anticolor e.g. $R\bar{G}$

QCD vertices.



3 gluon vertex

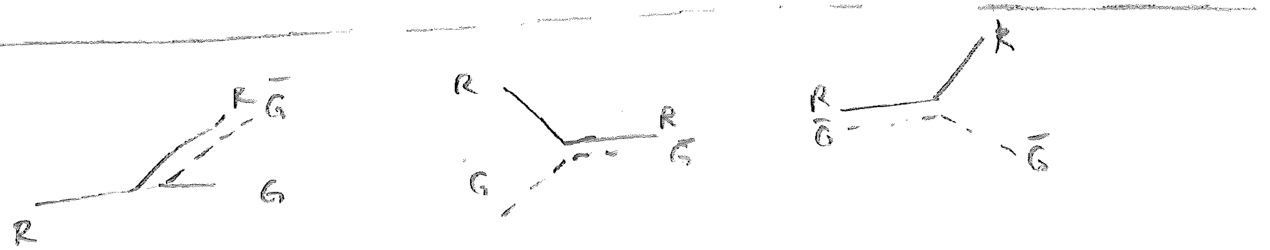


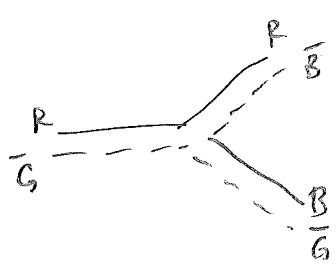
[NB Each color conserved at each vertex]

Double line notation for gluons:

$R\bar{G}$ ∼∼ =

vertices





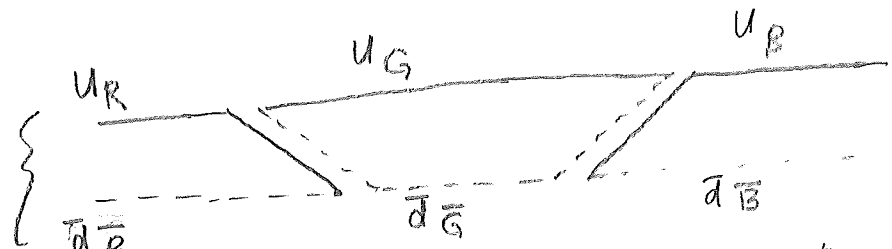
In SU(3) gauge theory there are various <u>neutral</u> combinations of color, e.g.

$$R\bar{R} + G\bar{G} + B\bar{B} \qquad \text{and} \qquad RGB$$

Confinement postulate: color force is so strong that only neutral combinations can appear in isolation.

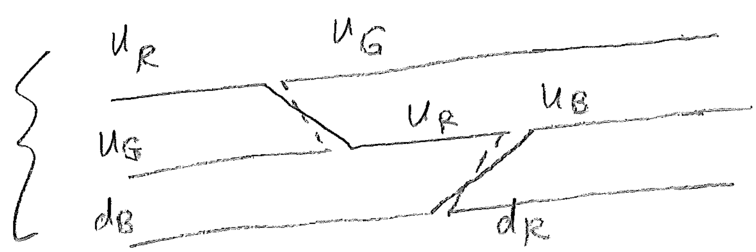
Quarks & gluons, which are not neutral, cannot appear in isolation [colored chalk here].

$\pi^+ =$



[So color of π^+ is really all combinations of $R\bar{R}$, $G\bar{G}$, $B\bar{B}$]

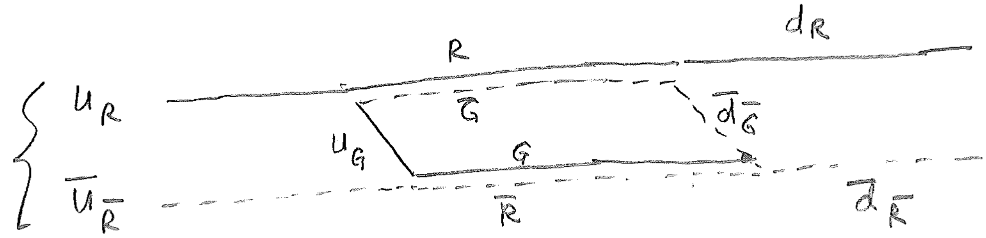
$p =$



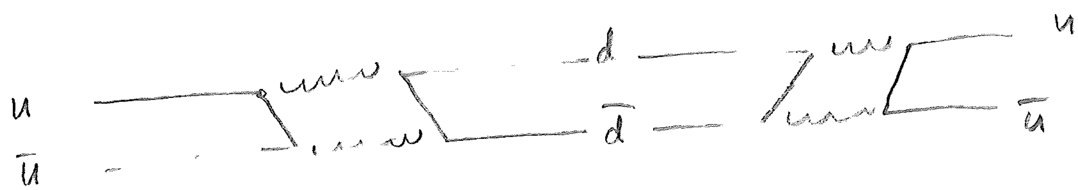
[Gluon exchange allows quarks to change color but overall color neutrality is maintained]

$$\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$$ ← what does this mean?

$\pi^0 =$



or just

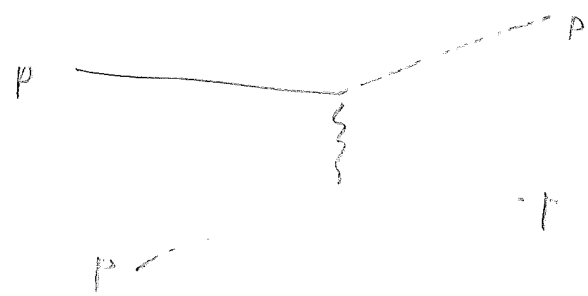


Thus neutral mesons are admixtures of $u\bar{u}$, $d\bar{d}$, $s\bar{s}$

[Henceforth we won't bother drawing colors]

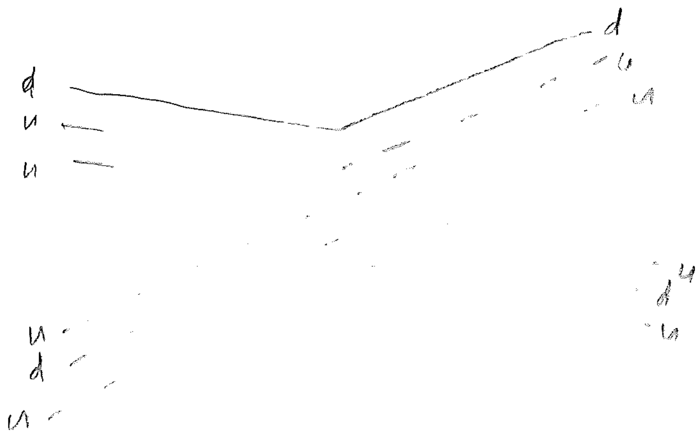
<u>Elastic</u> scattering of proton: $pp \rightarrow pp$

1) electromagnetic (long range $\frac{1}{r^2}$)

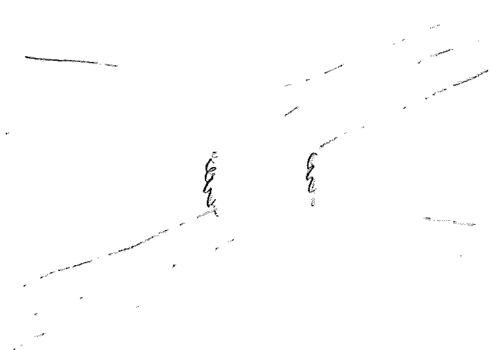


exchange of virtual γ
cause momentum transfer

2) strong: (short range ~ 1 fm) residual force between color neutral objects



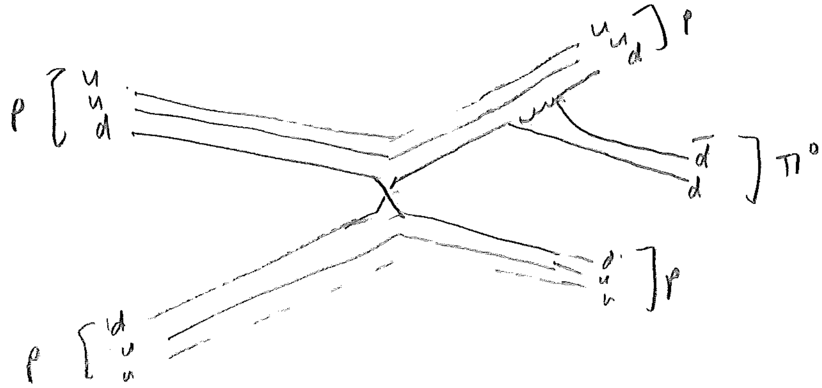
$8 \times 8 = 1 + \ldots$



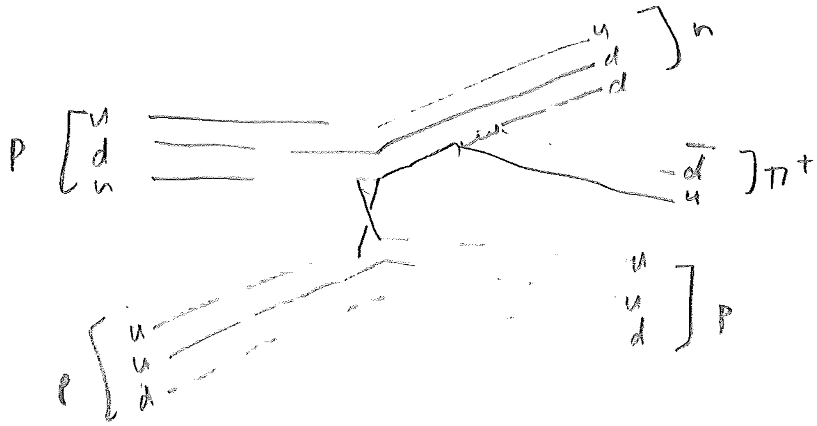
exchange of 2 gluons (not 1)

[Recall bremsstrahlung]

Inelastic scattering: $pp \to pp\pi^0$



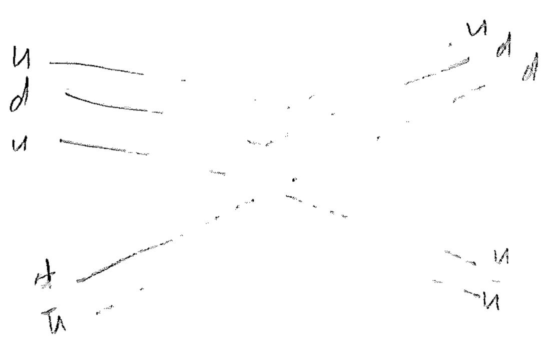
$pp \to np\pi^+$



Kinematically allowed if $E_{cm} \geq m_n + m_p + m_\pi$

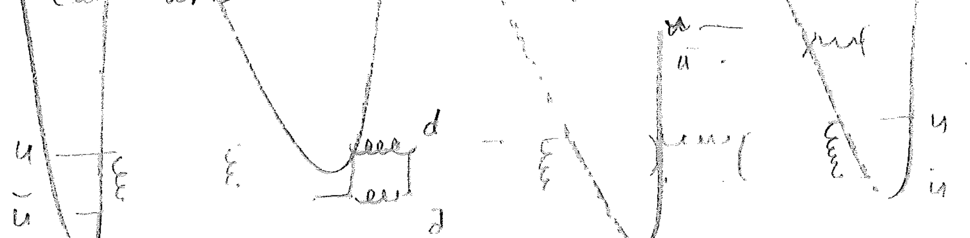
Pion production in cosmic rays & accelerators via strong force!

$\pi^- p \to n\pi^0$ (via exchange of quarks)



Q-1) old notes

[Can understand $\pi^0 = \frac{1}{\sqrt{2}}(u\bar{u} - d\bar{d})$ as due to mixing



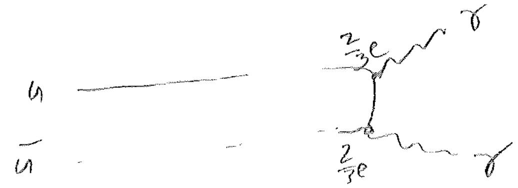
]

redo

π^0 decay

Like positronium, π^0 is unstable to EM decay

$\pi^0 \to \gamma\gamma$ $\quad (\tau \sim 10^{-16}s)$



$\Gamma \sim \left(\frac{2}{3}e\right)^2$

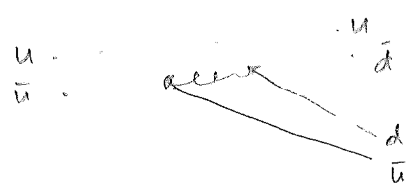
ρ^0 decay

Heavier mesons can also decay via EM but usually more likely to decay through strong force

$\rho^0 \to \pi^+\pi^-$. [kinematically allowed: $770 > 2(140)$]

Look up PPB: $\Gamma \sim 150\,\mathrm{MeV}$

$\Rightarrow \tau \sim 10^{-23}s$



$\rho^0 \to \pi^0\pi^0$

$\Gamma \sim (g_s)^2$

Because strong force coupling constant $g_s \gg e$

$\therefore \Gamma_{strong} \gg \Gamma_{EM}$ and so $\tau_{strong} \ll \tau_{em}$

typical $\tau_{strong} \sim 10^{-23}s$

[don't do $\eta, \eta' \to \pi\pi\pi$ decay]

Q 12

old nt

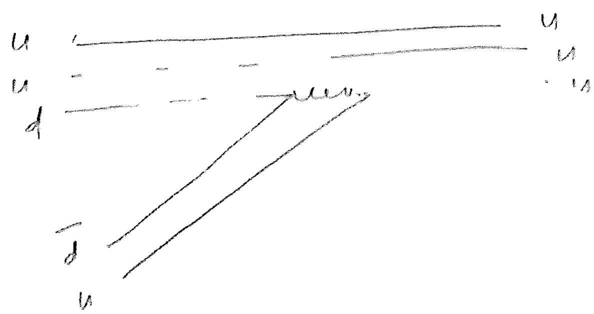
Heavier baryons also created in cyclotrons [Fermi 1951]

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

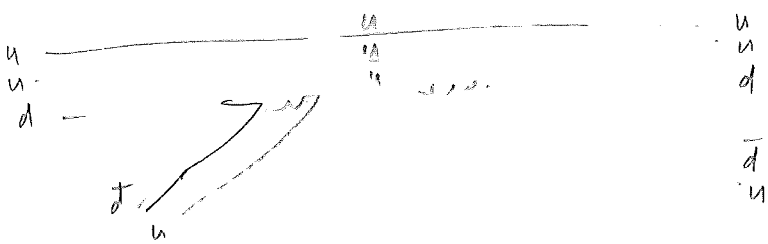
kinematically allowed if

$E_{cm} \gtrsim m_\Delta \sim 1230$ MeV

$(m_p + m_\pi \sim 1180$ MeV$)$

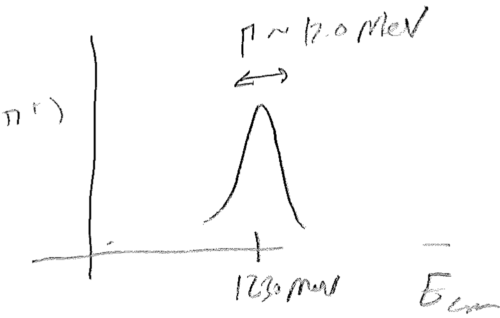


Δ^{++} decay just as quickly via strong force



Therefore Δ^{++} "observed" as resonance in $\sigma(p\pi^+ \to p\pi^+)$

$\sigma(p\pi^+ \to p\pi^+)$



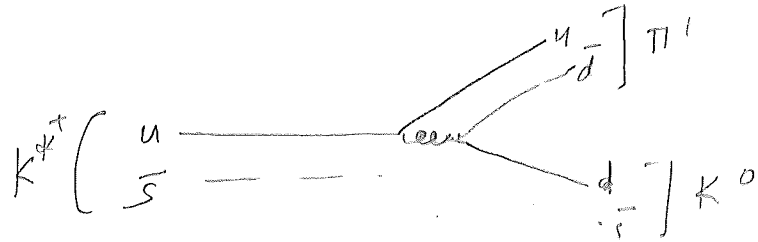
$$\Gamma \sim 120 \text{ MeV} \Rightarrow \tau = \frac{\hbar}{\Gamma} = \frac{6.6\times10^{-22} \text{ MeV sec}}{120 \text{ MeV}} \simeq 0.5\times10^{-23} \text{ s}$$

$c\tau \sim 1$ fm

Strangeness

Flavor quantum nos. are conserved in strong + EM interactions

Strangeness: $K^{*+} \longrightarrow K^0 \pi^+$ kinematically allowed
$892 > 495 + 140$



Since strong & EM interactions don't change flavor of quarks
the # of strange quarks does not change
$\Rightarrow$ strangeness is conserved in strong + em int'ns

• But K^0 cannot decay strongly because its the lightest strange hadron

Since $q = \frac{1}{2}(A + s) + I_3$

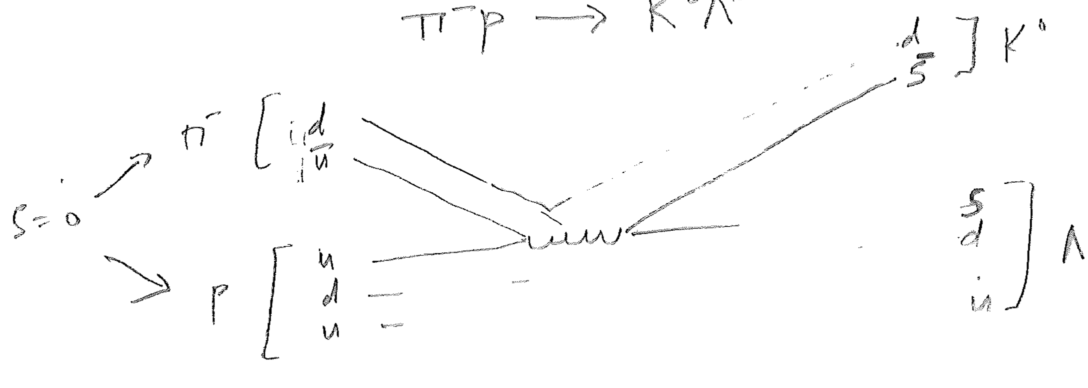
and since A & q are always conserved in standard model

$\Rightarrow I_3$ is also conserved in strong & EM int'ns

ie flavor is always conserved

If strangeness is conserved, how are strange particles even produced?
In equal & opposite pairs, via "associated production"

$\pi^- p \longrightarrow K^0 \Lambda^0$



$\leftarrow S \cdot 1$

$\leftarrow S \cdot -1$

HW problem

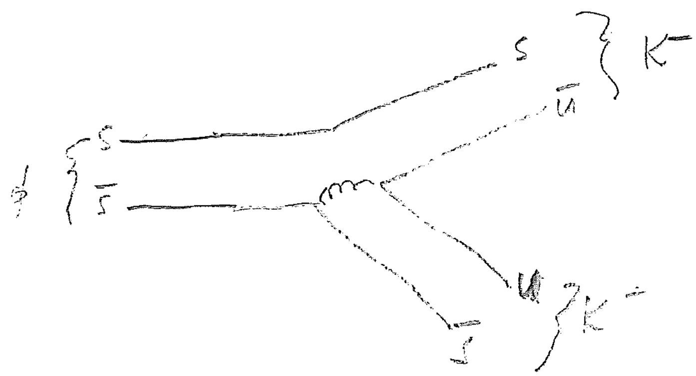
$\boxed{\phi(1020) = s\bar{s}}$

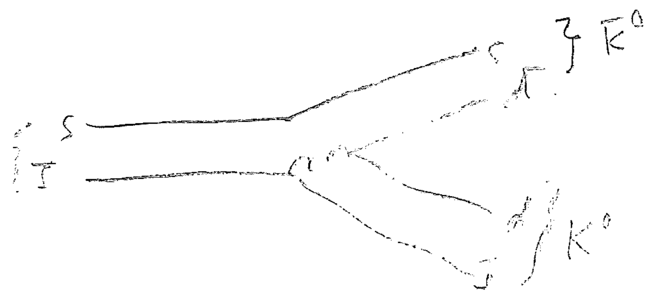
$m = 1020$ MeV

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

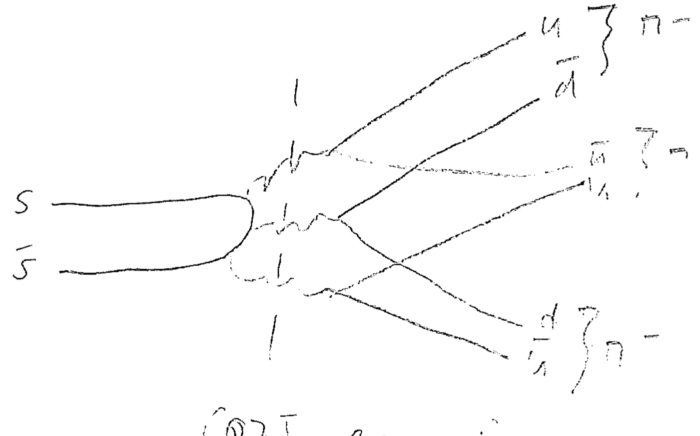
	BR	Q
$\phi \to K^+K^-$	49%	30 MeV
$\to K^0_L K^0_S$	34%	
$\to \pi^+\pi^0\pi^-$	15%	600 MeV

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





Could be considered associated production! (but ϕ already has $s\bar{s}$)



OZI suppressed

(Problem): ~~Show bary~~ for each member baryon decuplet; list all kinematically allowed strong interaction decay modes & draw F d.

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

$\Delta^+ \to p\pi^0,\ n\pi^+$

$\Delta^0 \to p\pi^-,\ n\pi^0$

$\Delta^- \to n\pi^-$

$\Sigma^{*+} \to \Sigma^+\pi^0,\ \Sigma^0\pi^+,\ \Lambda^0\pi^+$

$\Sigma^{*0} \to (\Sigma^0\pi^0)$ not $\Sigma^+\pi^-,\ \Sigma^-\pi^+,\ \Lambda^0\pi^0$

$\Sigma^{*-} \to \Sigma^-\pi^0,\ \Sigma^0\pi^-,\ \Lambda^0\pi^-$

$\Xi^{*0} \to \Xi^0\pi^0,\ \Xi^-\pi^+$

$\Xi^{*-} \to \Xi^0\pi^-,\ \Xi^-\pi^0$

$\Omega^- \overset{?}{\to} \Xi^- K^0$

Show no kinematically allowed decay to K's

Also electromagnetic (use PDB)

$\Sigma^0 \to \Lambda\ \gamma$

$\Xi \to \Xi\ \gamma$