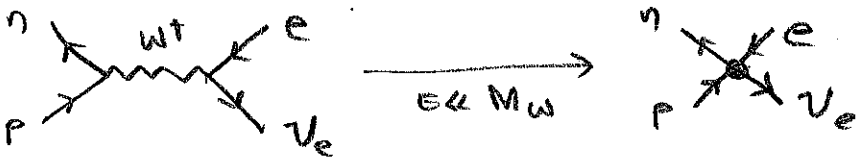
Today: Taylor - HIGGS VIA TOP COUPLINGS
QCD & CONFINEMENT

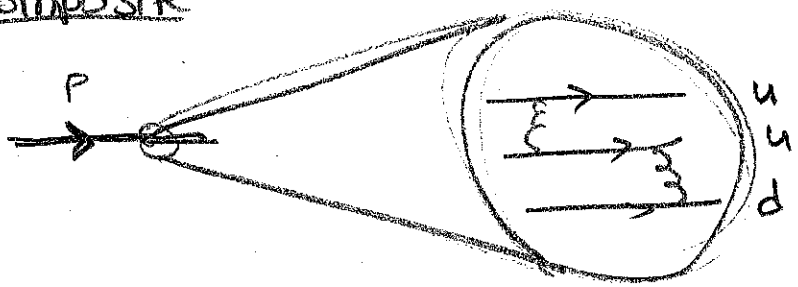
LAST WEEK: what is "fundamental"?

eg. interactions that are effective



BUT p & n ARE NOT EVEN FUNDAMENTAL PARTICLES

composite



∃ LH PROTON & RH PROTON ... effectively the same

@ $E \sim M_W$, you "see" individual quarks)

→ spin-$\frac{1}{2}$ combination of 3 quarks

color: neutral (EM)
charge: +1

$M_{pt} \sim 1$ GeV ← $\sim \Lambda_{QCD}$ "confinement scale"

Is this like hydrogen?

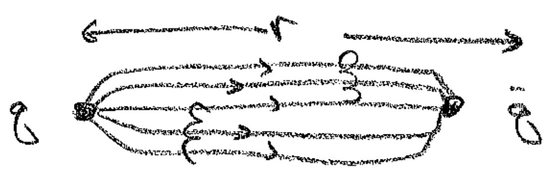
} weakly bound state
$V \sim \alpha/r$

color bound states are different: strongly bound

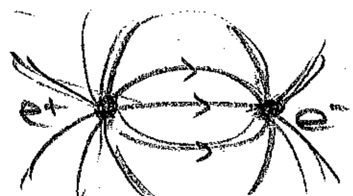
confined

"$V \sim r$" ← poetic

ENERGY INCREASES W/ COLOR CHARGE SEPARATION



vs.



confinement from self-interactions {

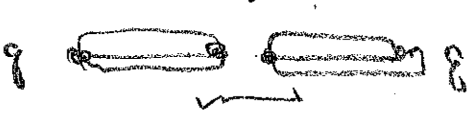
← self interactions of gluon field
→ flux tube

← electric field (no self-int.)

Nature wants to be color-neutral

← FLUX TUBE "SNAPS" when $E \gtrsim \Lambda_{QCD}$

just create a $\bar{q}q$ pair



$\bar{q}q$ PAIR

Why no SU(2) confinement?
Higgs breaks SU(2).

$V \sim \frac{e^{-m_Z r}}{r}$ ← exp. suppr.

So: NON ABELIAN FORCES TEND TO CONFINE @ LOW ENERGIES (unless Higgsed before it can do this

Resonances:

π^0 $u\bar{u} - d\bar{d}$ $m = 135$ MeV $J^P = 0^-$

ρ — $m = 775$ MeV $J^P = 1^-$

⋮

BUNCH OF OTHERS.

↑ COMPARE TO MASS OF CONSTITUENT QUARKS!

$m_{u,d} \sim 5$ MeV $\ll m_\pi$

MASS COMES FROM GLUON

Similarly: protons & neutrons, make up most of known matter

⇒ mass isn't from the 5 MeV of quark mass from Higgs!

comes from binding energy of QCD.

BUNCH 'O RESONANCES (particles)

→ distinguished by spin of composite particle.

→ also by flavor.

d & s quarks are identical except

d ↑ 5 MeV & stable

s ↖ 100 MeV & decays

→ FLAVOR

E ↑

$\gg M_t$: everything looks massless

↓ successive effective theories

LEN ↓

$\sim M_W \sim M_Z \sim M_H$

$SU(2) \times U(1) \to U(1)_{QED}$ (EWSB)

→ DIRAC FERMIONS w/ WELL DEF ELEC. CHARGE

→ WEAK FORCE BECOMES WEAK (short ranged)

BUNCH o PARTICLES

$\Lambda_{QCD} \leftarrow M_p$

color degrees of freedom confine

↳ BARYONS → 3 quarks (ε_{mnl})

↳ MESONS → quark/antiq. (δ^m_n)

Most of PDG are qcd <u>resonances</u>

analog of excited states

eg. B^0 $J^P = 0^-$ $M \approx 5.280$ GeV

B^* $J^P = 1^-$ $M \approx 5.320$ GeV

($d\bar{b}$)

↑ ORBITAL ANGULAR MOMENTUM

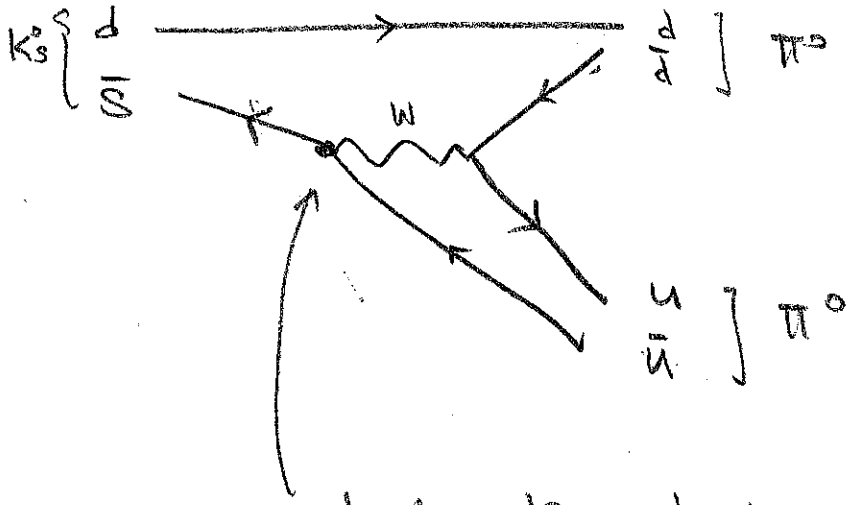
just like excited states of hydrogen.

$E^2 = M^2 + |\vec{p}^2|$ ← kinetic E of microstate appears to be mass E of bound state

So then you get diagrams like

$K_S^0 \to \pi^0 \pi^0$

$d\bar{s}$ ↑ ↖ ↑ $u\bar{u}$ or $d\bar{d}$ (quantum mix)



rate depends on how much 2ND GENERATION talks to 1st

	1st	2ND	3RD	← GENERATION
$Q = +2/3$	u	c	t	
$Q = -1/3$	d	s	b	

↑ We know there are actually four particles:

$Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, u_R, d_R$

Same for each Generation

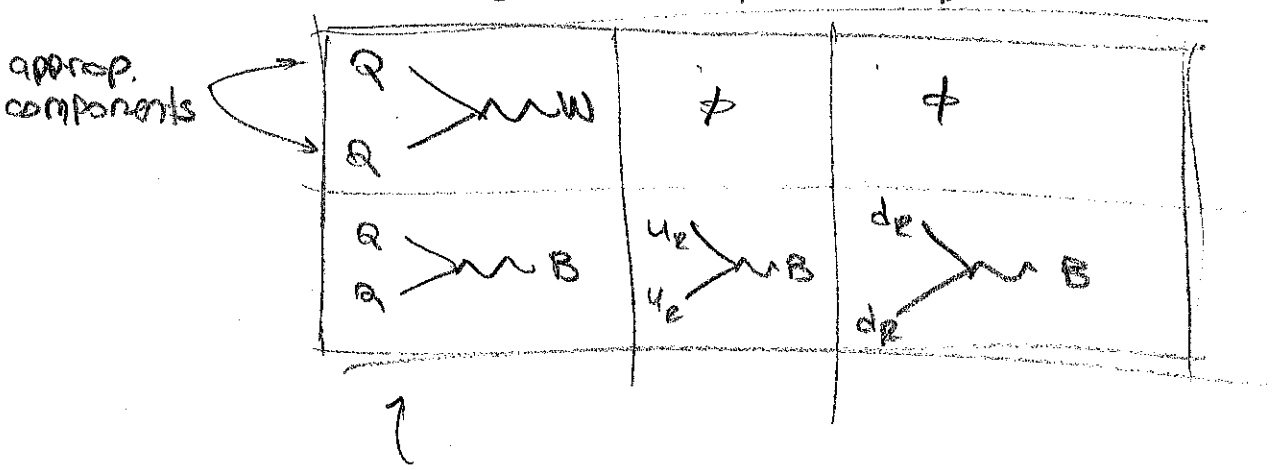
We know from 1 GEN model:

u_L ↘ W+

d_L ↗

Why does W talk between generations?

FLAVOR SYM: $Q^{(i)}$ $u_R^{(i)}$ $d_R^{(i)}$



"same-to-same" interaction
(GAUGE COUPLING)

BUT: YUKAWAS MESS THIS UP

$$y_{ij}^{(a)} Q^{(i)} d_R^{(j)} H^+ \to \frac{v y_{dij}^{(a)}}{\sqrt{2}} d_L^{(i)} d_R^{(j)}$$

MASS MATRIX BUT NOT DIAGONAL

ROT. IN FLAVOR SPACE

$Q = U_q \hat{Q}$ ← rotates the d_L

$d_R = U_d \hat{d}_R$

s.t. $\frac{v}{\sqrt{2}} (U_q y U_d)_{ij}$ is DIAGONAL

COOL WHAT ABOUT UP QUARKS?

$$y^{(u)}_{ij}\, Q^{(i)}\, u_R^{(j)}\, (\epsilon H) \longrightarrow \frac{v}{\sqrt{2}}\, y^{(u)}_{ij}\, u_L^{(i)}\, u_R^{(j)}$$

(ϵH): lowers SU(2) index to contract w/ Q

another off diagonal matrix.

DIAGONALIZE AGAIN

$$u_R = U_u\, \hat{u}_R$$

$$\boxed{Q = U'_Q\, \hat{Q}}$$ ← CANNOT DO THIS TO ROTATE u_L!

↑ we already used up this freedom to rotate d_L!!

What to do?
ROTATE u_L ANYWAY. WE KNOW IT SHOULD HAVE A WELL DEFINED MASS.

$$Q^{(i)} = U^{i}_{Q\,j}\left(\boxed{[\Delta U]^{j}_{\ k}}\ \hat{u}_L^{\,k} \atop d_L^{\,j}\right)$$

ADDITIONAL ROTATION

* doesn't matter if you put ΔU on u_L or d_L. I THINK I'VE DONE IT OPPOSITE TO USUAL CONVENTION.

MASS TERMS ARE DIAGONAL. WHAT'S THE COST?

$$\bar{Q}\, i\not{D}\, Q = \bar{\hat{Q}}\,\boxed{U_Q^{\dagger}}\, i\not{D}\,\boxed{U_Q}\, Q$$

CANCEL (act on flavor indices)

$$= (\hat{u}_L^{\dagger}(\Delta U)^{\dagger}_{ij}\ \hat{d}_L^{\dagger})\ i\not{D}\begin{pmatrix}\Delta U\, u_L \\ d_L\end{pmatrix}$$

Z_0 and so: diagonal terms are unaffected (γ, W^3, B)

eg. $\hat{u}_L^\dagger \boxed{(\Delta U)^\dagger}\, i\gamma^\mu \partial_\mu \boxed{(\Delta U)}\, u_L$

↑ acts on spin indices

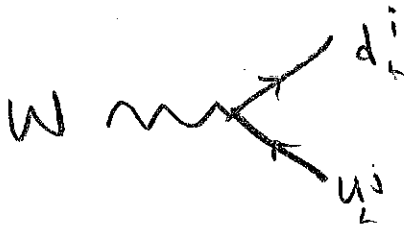
CANCEL (act on flavor matrices)

but: $\hat{d}_L^\dagger\, ig\gamma^\mu W_\mu^- \boxed{(\Delta U)}\, u_L$

↑ not canceled!

$\hat{d}_L^{\dagger(i)}\, ig\gamma^\mu W_\mu^- \boxed{(\Delta U)_{ij}}\, u_L^{(j)}$

↑ matrix of interactions



$\sim ig\gamma^\mu (\Delta U)_{ij}$

↑ in general, non zero for all elements

eg $u^1 = u$	$u^2 = c$	$u^3 = t$
$d^1 = d$	$d^2 = s$	$d^3 = b$