Lecture # 6.

2 slides from L#5

mass term for "electron"

$$L = -G_e\Big[\underbrace{\underbrace{(\bar\nu_e,\bar e)_L}_{SU(2)\,double}\underbrace{\begin{pmatrix}\varphi^+\\ \varphi^0\end{pmatrix}}_{SU(2)\,double}}_{SU(2)\,singl} \underbrace{e_R}_{SU(2)\,singl} + \bar e_R(\varphi^-,\bar\varphi^0)\begin{pmatrix}\nu_e\\ e\end{pmatrix}_L\Big]$$

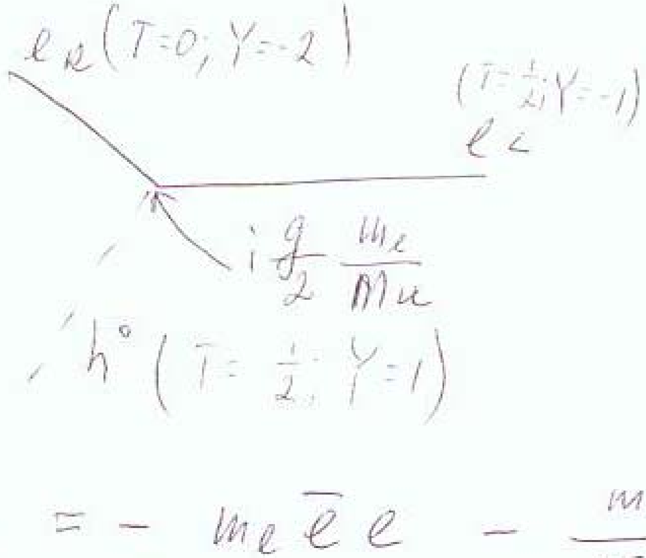
SU(2) singl all!

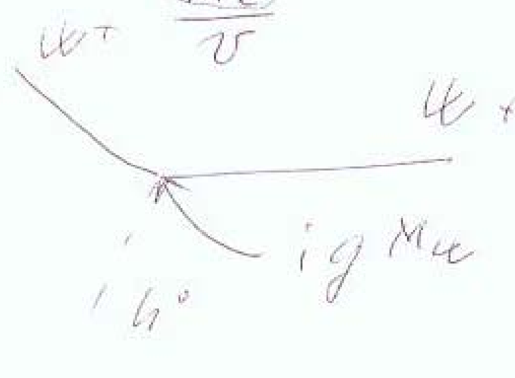
$$\varphi = \frac{1}{\sqrt2}\begin{pmatrix}0\\ v+h(x)\end{pmatrix}$$

$$L = \underbrace{-\underbrace{\frac{G_e}{\sqrt2}v}_{m_e}\left(\bar e_L e_R + \bar e_R e_L\right)}_{mass\ term} - \underbrace{\overbrace{\frac{G_e}{\sqrt2}}^{\frac{m_e}{v}}\left(\bar e_L e_R + \bar e_R e_L\right)h}_{\substack{interaction\\ with\ h\text{-}field}}$$

$$m_e = \frac{G_e v}{\sqrt2}$$

coupling to h $\frac{m_e}{v}$





$$L = -m_e\bar e e - \frac{m_e}{v}\bar e e h$$

$G_e = \frac{\sqrt2\, m_e}{v}$ – arbitrary coupling constant
m_e not predicted!

Note that neutrino did not get any mass in this mechanism $\longrightarrow \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$

What about quarks?
both up-type & down-type quarks have mass.
We must construct a new Higgs doublet from φ to meet the needs of the "upper" family

neutral

$$\varphi_c = -i\tau_2\varphi^* = \begin{pmatrix} -\bar{\varphi}^0 \\ \varphi^- \end{pmatrix} \xrightarrow{\text{breaking}} \frac{1}{\sqrt{2}} \begin{pmatrix} v + h(x) \\ 0 \end{pmatrix}$$

charged

φ_c transforms identical to φ

$$Y(\varphi_c) = -1 \qquad Y(\varphi) = 1$$

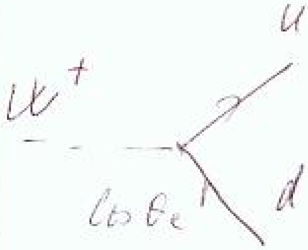
$$L = -G_d (\bar{u}, \bar{d})_L \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} d_R - G_u (\bar{u}, \bar{d})_L \begin{pmatrix} -\bar{\varphi}^0 \\ \varphi^- \end{pmatrix} u_R + h.c. \overset{\text{after breaking}}{=}$$

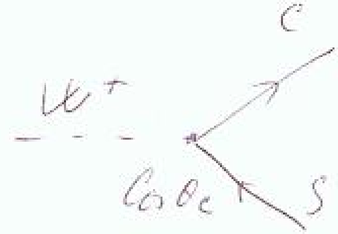
$$= -m_d \bar{d} d - m_u \bar{u} u \underbrace{- \frac{m_d}{v} \bar{d} d h - \frac{m_u}{v} \bar{u} u h}_{\text{interaction with } h}$$

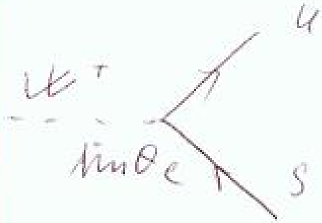
$$m_f = \frac{G_f v}{\sqrt{2}}$$

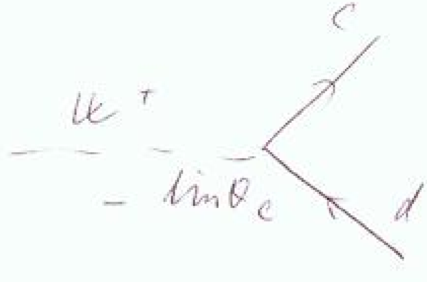
Done? Not yet...
Remember Cabibbo-Kobayashi-Maskawa?
weak iso-doublets of quarks $\neq$ mass eigenstates! Need to rotate by CKM

For two generations:



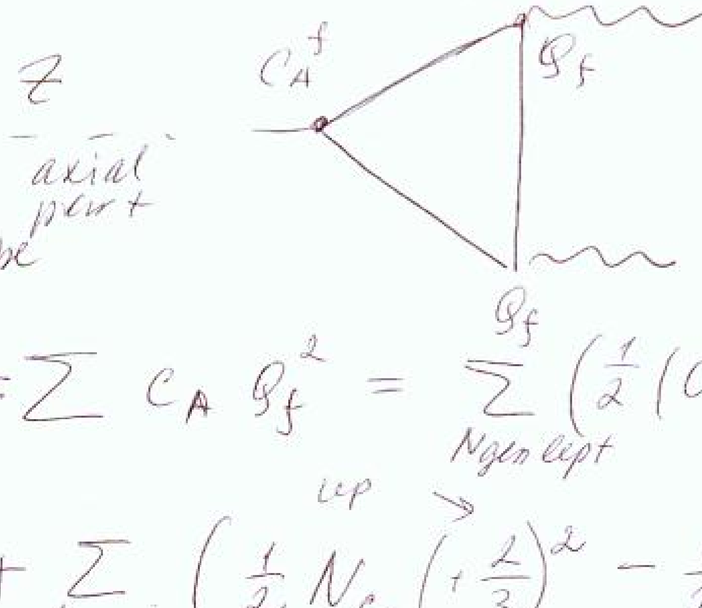






$$\theta_c \approx 13^\circ$$

We actually have three generations.
$\theta_c \Rightarrow$ 3 × 3 matrix CKM.
On a side note. Why the number of leptonic generations must be equal to the number of quark generations.
divergent diagram $\Rightarrow$ need to cancel



$$C_A^f = T_f^3$$

$$\overset{\text{must be}}{0} = \sum C_A Q_f^2 = \sum_{N_{gen\,lept}} \left(\tfrac{1}{2}(\overset{\nu}{0})^2 - \tfrac{1}{2}(\overset{e}{-1})^2\right) +$$

$$+ \sum_{N_{gen\,q}} \left(\tfrac{1}{2} \underbrace{N_c}_{\text{number of colors}} \left(\overset{\text{up}}{+\tfrac{2}{3}}\right)^2 - \tfrac{1}{2} N_c \left(-\tfrac{1}{3}\right)^2\right) =$$

Wow, we do need 3 colors! $\to 1/3$

$$= -\frac{1}{2} N^{lept} + \frac{1}{2} N_c \cdot N^{q} \cdot \left(\frac{4}{9} - \frac{1}{9}\right) =$$

$$= -\frac{1}{2} N^{lept} + \frac{1}{2} N^{quark} \Longrightarrow$$

$$\Longrightarrow N_{lept} = N_{quarks} \; !$$

back to EW Lagrangian

$$L = - G_d^{ij} \left(\bar{u}_i \, \bar{d}_i'\right)_L \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix} d_{jR} -$$

CKM rotated

right handed quarks do not participate in SU(2) interactions, not rotated

$$- G_u^{ij} \left(\bar{u}_i \, , \bar{d}_i'\right)_L \begin{pmatrix} -\bar{\varphi}^0 \\ \varphi^- \end{pmatrix} u_{jR} + h.c.$$

$i, j = 1, \ldots N$ - number of quark doublets.

diagonalizing in 3×3 quark space

$$L = -m_d^i \bar{d}_i d_i \left(1 + \frac{h}{v}\right) - m_u^i \bar{u}_i u \left(1 + \frac{h}{v}\right)$$

$$m_f^i = \frac{G_f v}{\sqrt{2}}$$

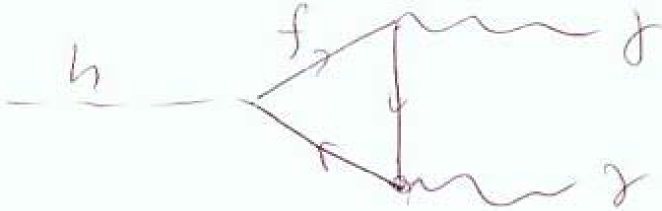
So, higgs couples to

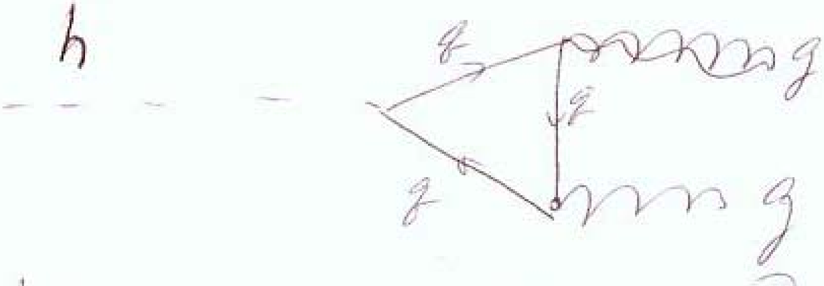
- W^+W^- $\propto m_W$
- ZZ $\propto m_Z$
- hh
- hhh
- hWW
- hZZ

and fermions

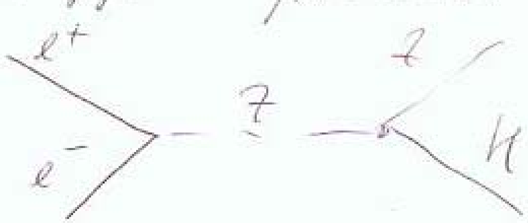
- $f\bar{f}$ $\propto m_f$

does not directly couple to γ, or g, but loops work.

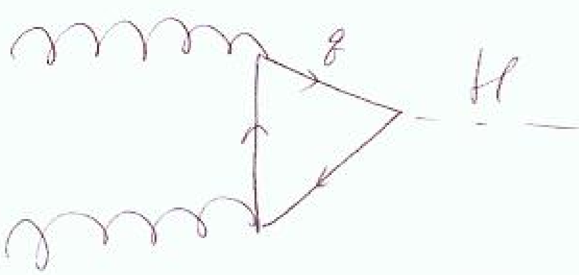


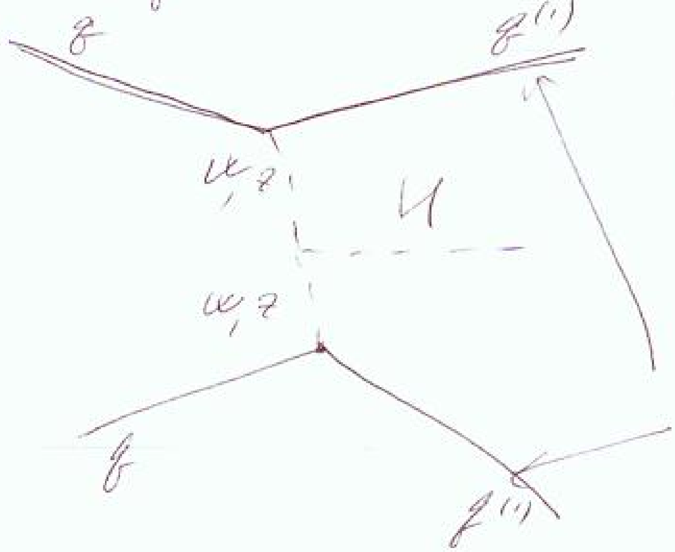


higgs production @ e^+e^-



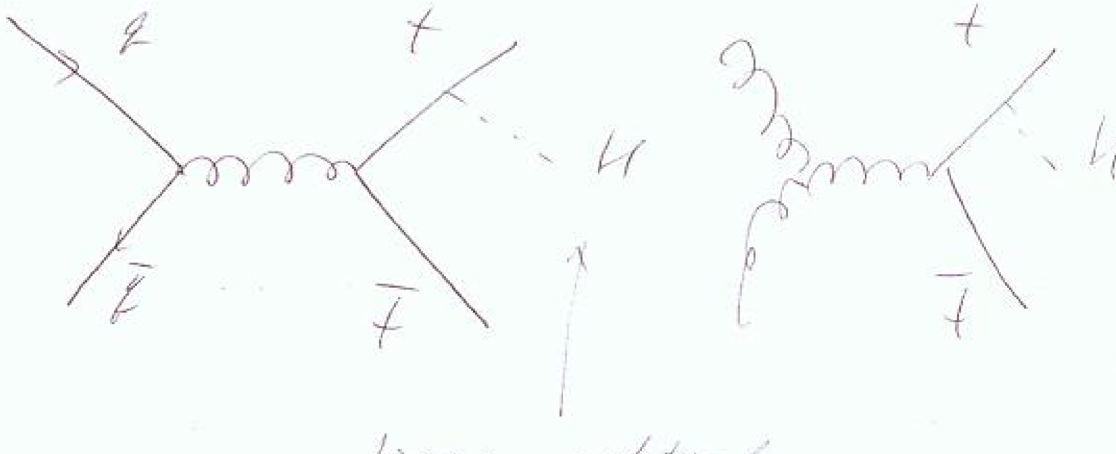
Higgs production at $\bar{p}p$, pp





VBF = vector boson fusion

forward energetic jet



higgs schtralung

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Higgs decays

Low mass Higgs

$$H \to \begin{array}{l|l} b\bar{b} & \\ \tau\bar{\tau} & \\ c\bar{c} & \text{tree level} \\ \hline gg & \text{loops} \\ \gamma\gamma & \end{array}$$

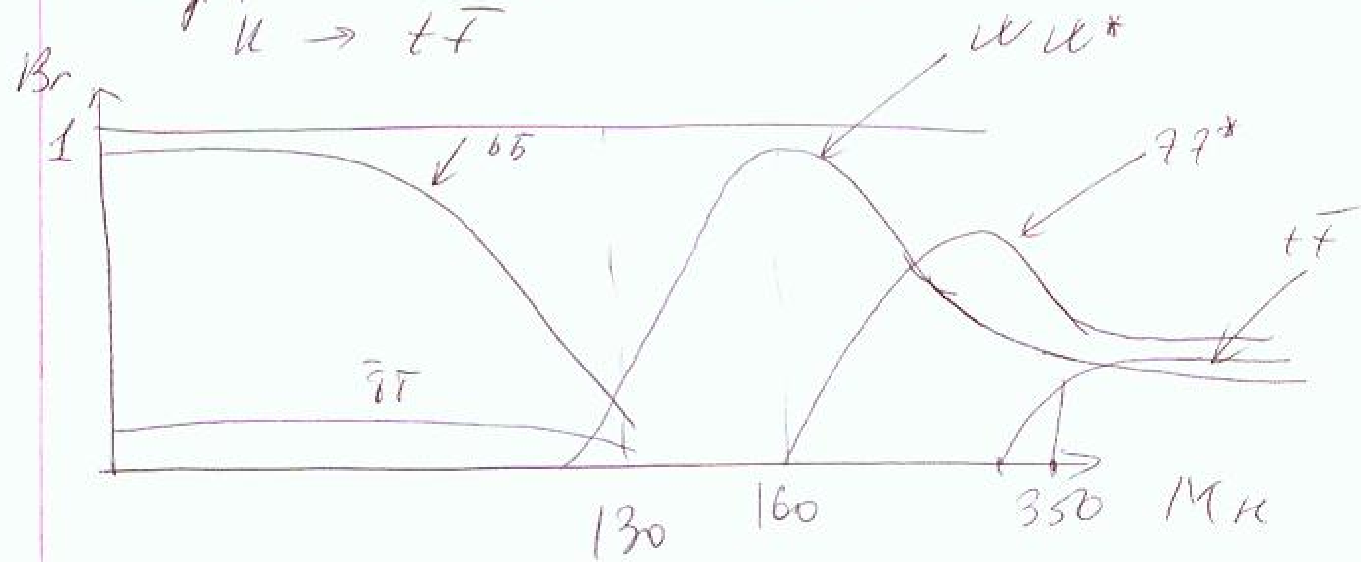
(coupling proportional to mass)

Intermediate mass Higgs

$$H \to W\,W^{(*)}$$
$$\quad\;\; Z\,Z^{(*)}$$

high mass - add

$$H \to t\bar{t}$$



Experimental constraints on M_H from M_W & M_t

$M_W =$