Title: Particle Physics Lecture - 230315

Speakers:

Collection: Particle Physics (2022/2023)

Date: March 15, 2023 - 11:30 AM

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Mutual information

$$I(X,Y) := H(X) + H(Y) - H(X,Y)$$

$$\|$$

$$I(X,Y) := H(Y) - H(Y|X)$$

$$H(Y|X) = -\sum_{\substack{x \in X \\ y \in Y}} p(x,y) \, \mathrm{Log} \frac{P(x,y)}{P(x)}$$

$P(x|y)$

FLAVOR?

Flavors, families
generations

Each SM particle comes in 3 <u>copies</u>

- same gauge int.
- different masses

u^i	u_1	u
	u_2	c
	u_3	t

Flavors, families
generations

comes in 3 copies
same gauge int.
different masses

u^i	u_1	u	$m \sim 2\,\mathrm{MeV}$
	u_2	c	$m_c \sim 1.3\,\mathrm{GeV}$
	u_3	t	$m_t \sim 170\,\mathrm{GeV}$
d		d	$m \sim 4\,\mathrm{MeV}$
		s	$m_s \sim 0.9\,\mathrm{GeV}$
		b	$m_b \sim 4.2\,\mathrm{GeV}$

GeV
V
GeV
eV

interesting

- 6 orders : $m_e \sim 511$ keV $\longrightarrow m_t \sim 170$ GeV
- $m_3 \gg m_2 \gg m_1$

FLAVOR PROBLE

$$-\frac{1}{4} G^a_{\mu\nu} G^{a\,\mu\nu} + \dots$$

$$\sum_i \sum_\psi \bar{\psi}^i \, i \not{D} \, \psi^i \qquad \psi = \{ q_L, \ell_L, e_R, d_R, u_R \}$$

$$\mathcal{L}_{SM} = \underbrace{\mathcal{L}_g + \mathcal{L}_f}_{\text{GAUGE SECTOR}} + \underbrace{\mathcal{L}_H + \boxed{\mathcal{L}_Y}}_{\text{HIGGS SECTOR}}$$

$$\mathcal{L}_Y = - \bar{q}_L^i Y_d^{ij} H \dots$$

- Completely fixed by gauge & matter content

$\longrightarrow$ 3 free par: g_s, g_L, g_Y

$$D_\mu H^\dagger D^\mu H - V(H)$$

$$H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}$$

- $G_f = U(3)^5 = U(3)_{q_L} \times U(3)_{\ell_L} \times \dots \qquad q_L \to U q_L$

$$\sum_i \sum_\psi \bar\psi^i \, i\not{D} \, \psi^i \qquad \psi = \{q_L, \ell_L, e_R, d_R, u_R\}$$

$$\tilde H = i\sigma_2 H^*$$

$$\mathcal{L}_f + \underbrace{\mathcal{L}_H + \boxed{\mathcal{L}_Y}}_{\text{Higgs SECTOR}}$$

$$\mathcal{L}_Y = - \bar q_L^i Y_d^{ij} H d_R - \bar q_L y_u^{ij} \tilde H u_R - \bar \ell_L^i y_e^{ij} H$$

E

R

$$D_\mu H^\dagger D^\mu H - V(H)$$

ed

ter content

$$\boxed{H = \begin{pmatrix} 0 \\ \frac{v+h}{\sqrt{2}} \end{pmatrix}}$$

g_s, g_L, g_Y

$$U(3)_{q_L} \times U(3)_{\ell_L} \times \qquad q_L \to U q_L$$

$e_R, d_R, u_R \}$

$$\tilde{H} = i\sigma_2 H^*$$

$$\mathcal{L}_Y = - \bar{q}_L^i Y_d^{ij} H d_R - \bar{q}_L y_u^{ij} \hat{H} u_R - \bar{l}_L^i y_e^{ij} H \bar{e}_R^j$$

ONLY SM int

DiA

$\boxed{\text{DIAGONALIZE}}$ $\forall$ M hermitian $\exists$ $\mathcal{U}$ unitary $|$ $U^{\dagger} M U = \hat{M} \longrightarrow$ REA

m

$\forall \; Y_d \;\; \exists \;\; L_d, R_d$ unitary $|$ $L_d^{\dagger} Y_d R_d = \hat{Y}_d = \mathrm{diag}(y_d, y_s, y_b)$

$Y_u \;\; L_u, R_u$

$Y_e \;\; L_e R_e$

$\tilde{H} = i\sigma_2 H^*$

$\tilde{H}\, u_R \quad - \quad \bar{l}_L^{\,i}\, y_e^{ij} H\, \bar{e}_R^{\,j}$ ONLY SM int. that "sees" flavor

DIAGONAL

an $\exists\ \mathcal{U}$ unitary $\big|\ U^{+} M U = \hat{M} \longrightarrow$ REAL, POSITIVE EV

$L_d^{+}\, Y_d\, R_d = \hat{Y}_d = \mathrm{diag}(y_d, y_s, y_b)$ $\quad m_i = y_i \dfrac{v}{\sqrt{2}}$

$$L_d^\dagger Y_d R_d = \hat{Y}_d \to Y_d = L_d \hat{Y}_d R_d$$

$$\mathcal{L}_Y = -\bar{q}_L L_d \hat{Y}_d R_d^\dagger H d_R - \bar{q}_L (L_u \hat{Y}_u R_u^\dagger) \tilde{H} u_R + \dots$$

use $U(3)^5$ symm to rotate the fields & remove as many L,R as possible without

$$q_L \to L_d q_L$$

$$= -\bar{q}_L \hat{Y}_d H d_R - \bar{q}_L \underbrace{(L_d^\dagger L_u)}_{V_{CKM}} \hat{Y}_u u_R \tilde{H}$$

$$\frac{g_L}{2} W_\mu^+ \bar{u}_L \gamma d_L \Longrightarrow \frac{g_L}{2} W_\mu^+ \bar{u}_L V \gamma d_L + hc$$

$u \to d$

$c \to s$

$t \to b$

Source of ALL FC int. in the SM

(Yukawa sector)

$$\underset{\text{unitary}}{N \times N} \longrightarrow N^2 \begin{cases} \dfrac{N(N-1)}{2} & \text{angles} \\ \dfrac{N(N+1)}{2} & \text{phases} \end{cases}$$

CKM: $9 = 3$ angles, 6 phases

$\boxed{\text{BUT}}$ ONLY 4 ARE PHYSICAL

$$G_f = U(3)_{q_L} \times U(3)_{d_L} \times U(3)_{u_L}$$

$$N_{broken} = \dim G_f - \dim G_f' = 27 = 9 \text{ angles} + \ldots$$

3×3 A $\quad 1$ P

6×3 P

$$G_f' = U(1)_B$$

-1) angles

+1) phases

6 phases

YSICAL

$(3)_{\nu_L}$

$$N_{tot} = 36 = 18 \text{ angles} + 18 \text{ phases}$$

$$N_{broken} = \dim G_f - \dim G_f' = 27 = 9 \text{ angles} + 17 \text{ phase}$$

3×3 A 1P

6×3 Γ

CKM 4 parameters

PDG $\theta_{12}, \theta_{23}, \theta_{13}, \delta$

Wolfenstein A, ρ, η, λ

$$N_{dof} = N_{tot} - N_{br}$$

$$= 9 \text{ angles} + 1 \text{ phase}$$

6 quark masses

3 CKM angles

511 keV $\rightarrow m_t \sim 170$ GeV

$$V^\dagger V = \mathbb{1}$$

$$\sum_k V_{ki} V_{kj}^* = \delta_{ij}$$

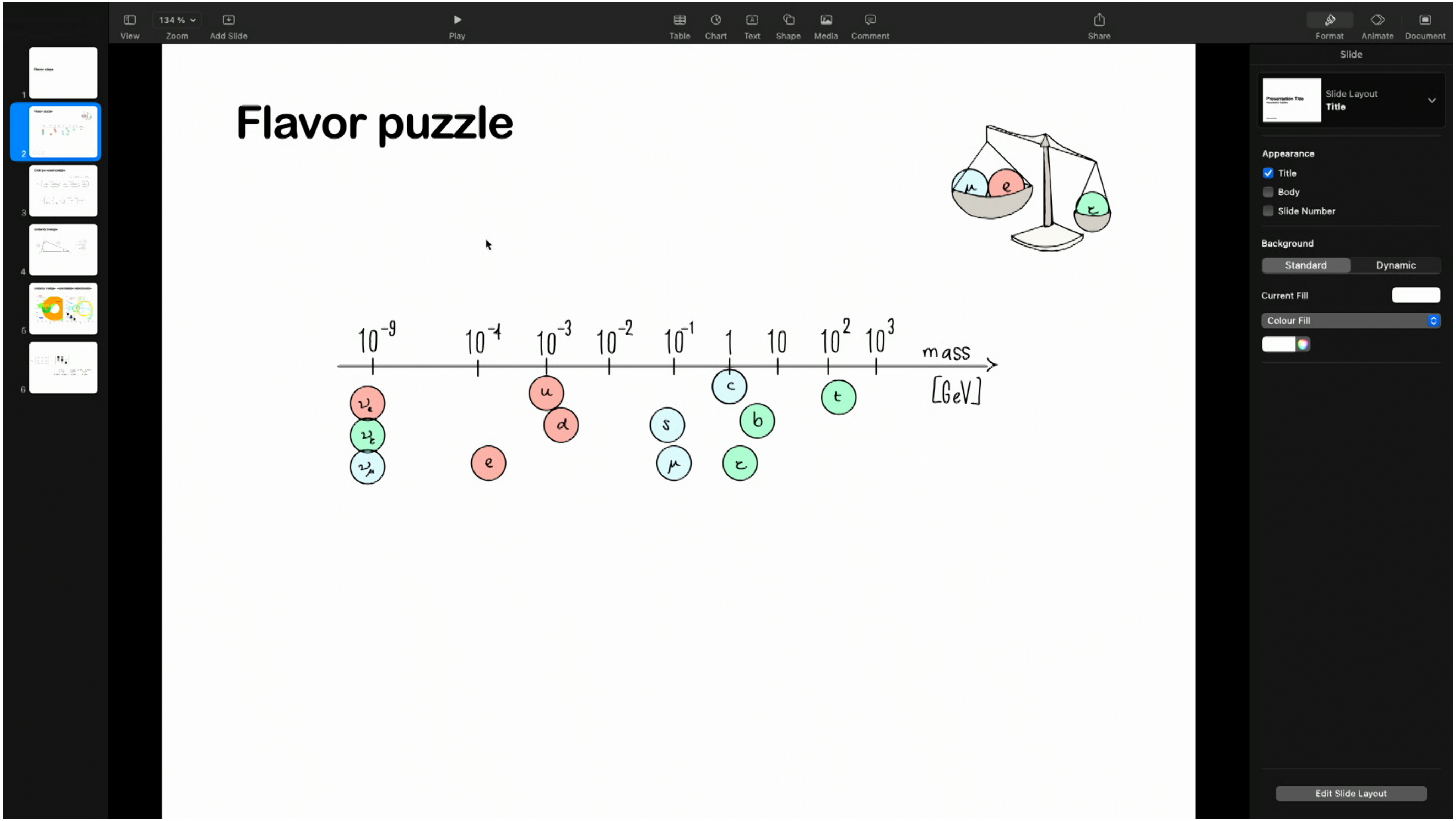
$i \neq j$

$i = 1, j = 3$

$$V_{ud} V_{ub}^* + V_{td} V_{tb}^* + V_{cd} V_{cb}^* = 0$$

$$\rho + i\eta + (1 - \rho - i\eta) + 1 = 0$$

"triangle" (ρ, η) plane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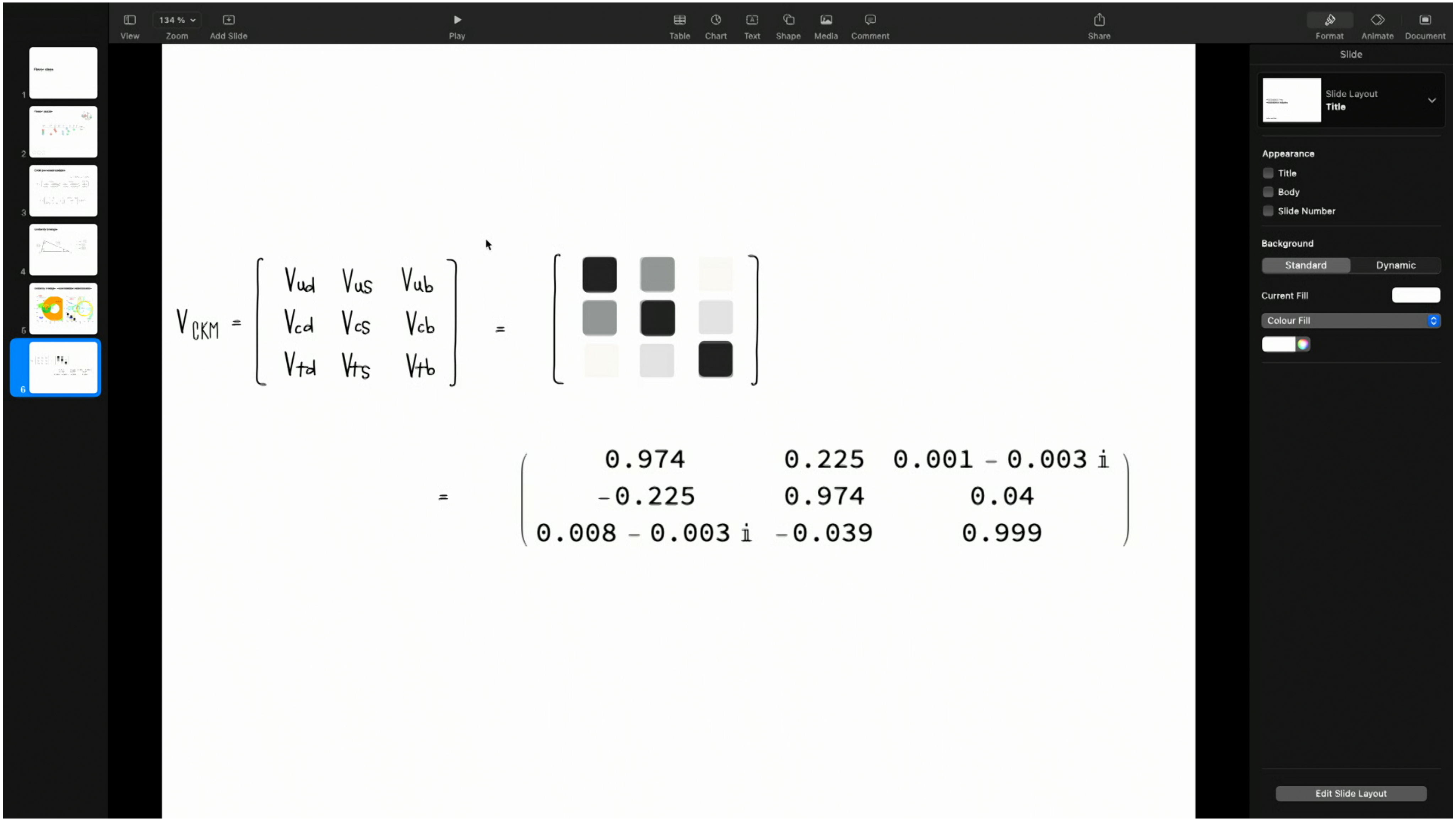
CKM parametrizations

$$s_{ij} = \sin\theta_{ij},\ c_{ij} = \cos\theta_{ij}$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{13}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$V = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{\lambda^2}{2} & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)\,.$$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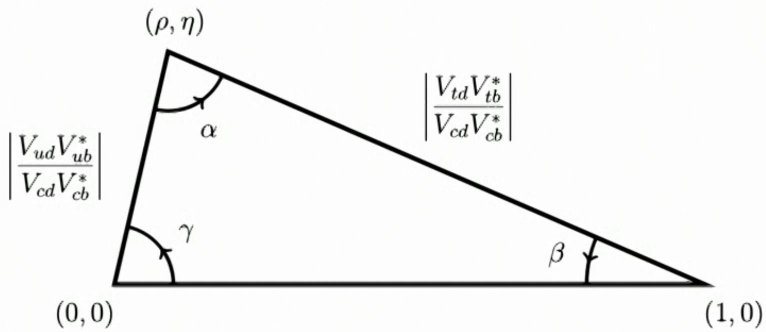
$V_{CKM} = \begin{bmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{bmatrix} =$
$= \begin{pmatrix} 0.974 & 0.225 & 0.001 - 0.003\,i \\ -0.225 & 0.974 & 0.04 \\ 0.008 - 0.003\,i & -0.039 & 0.999 \end{pmatrix}$

Unitarity triangle



$$\alpha = \arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$$
$$\beta = \arg\left(\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right)$$
$$\gamma = \arg\left(\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right).$$

us

FCCC $u \to s$ $|\Delta Q| = 1$ tree level $K^- \to \mu^- \nu$ $BR = 0{,}64$

sd

FCNC $d \to s$, $u \to c$ $\Delta Q = 0$ start at 1 loop → loop suppressed "RARE DECAYS" $K_L \to \mu^+ \mu^-$ $BR \sim 7 \cdot 10^{-9}$

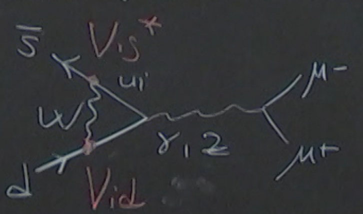
e.g. $B \to D \ell \nu$

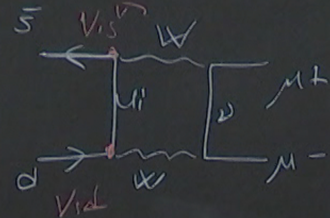
$B \to K \mu \mu$

GIM MECHANISM

"in FCNC loops, the amplitude is at least quadratic in the internal quark masses"

$K_L \to \mu^+\mu^-$



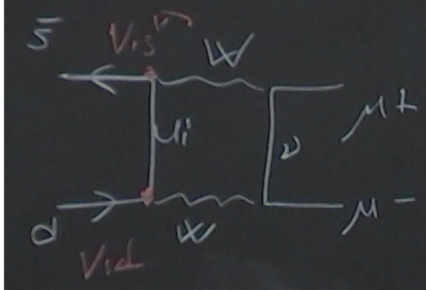


$$A \sim \frac{g^4}{16\pi^2}\frac{1}{m_t^2}\sum_i \underbrace{V_{is}^* V_{id}}_{\lambda_{sd}^i} f(m_i^2)$$

$\lambda^u_{sd}+\lambda^c_{sd}+\lambda^t_{sd}=0$

$$\left[\underbrace{\lambda^c_{sd}}_{0.2}\left(f(m_c^2)-\cancel{f(m_u^2)}\right) + \underbrace{\lambda_t^{sd}}_{3\cdot10^{-4}}\left(f(m_t^2)-f(\cancel{m_c^2})\right)\right]$$

...plitude is at least quadratic in the internal quark masses !!



$f(m_i^2)$ $\qquad \lambda^u_{sd} + \lambda^c_{sd} + \lambda^t_{sd} = 0$

$$\ldots m_t^2) - \cancel{f(m_u^2)} \Big) + \underline{\underline{\lambda_t^{sd}}} \left(f(m_t^2) - \cancel{f(m_c^2)} \right) \Big]$$

$3 \cdot 10^{-4}$

$$A \cong \underbrace{\frac{g^4}{16\pi^2}}_{\text{Loop suppr}} \frac{1}{m_Z^2} \overbrace{V^*_{cs} V_{cd} \frac{m_c^2}{m_W^2}}^{\text{GIM}}$$

$$\sim \frac{G_F^2}{16\pi^2} \lambda\, m_c^2$$

u, d, s $\quad A(K_L \to \mu\mu) \sim \frac{G_F^2}{16\pi^2} \lambda \Lambda^2$

$\Lambda \sim 2\text{-}3\ \mathrm{GeV} \qquad \Lambda_{nat} \sim G_F^{-1/2} \sim 300\ \mathrm{GeV}$