Title: Standard Model Lecture

Speakers: Michael Trott

Collection: Standard Model 2023/24

Date: January 29, 2024 - 3:15 PM

URL: https://pirsa.org/24010040

CP violation

$$V_{CKM} = \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda(\rho - i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$$\varepsilon \sim O(10^{-1}) \simeq \begin{pmatrix} \varepsilon^0 & \varepsilon & \varepsilon^3 \\ \varepsilon & \varepsilon^0 & \varepsilon^2 \\ \varepsilon^3 & \varepsilon^2 & \varepsilon^0 \end{pmatrix}$$

$\lambda(\rho - i\eta)$

λ^2

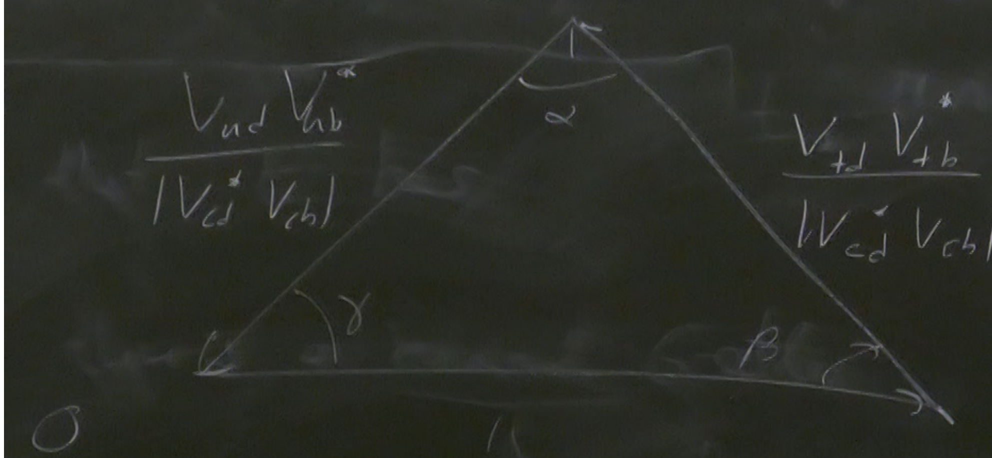
→ phase convention independent measure of CP violation

Unitarity triangles $\quad V^\dagger_{CKM} V_{CKM} = \mathbb{1}$

$|weak\rangle \to |mass\rangle$ $\quad \sum_k |V_{jk}|^2 = 1 \, , \quad \sum_k V_{ik} V^*_{jk} = 0$

$U(\psi, L/R)$

unitary $U^\dagger U \to$ unitary



$$\alpha = \arg\left[-\frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*}\right]$$

$$\beta = \arg\left[-\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*}\right]$$

$$\gamma = \arg\left[-\frac{V_{cd} V_{cb}^*}{V_{cd} V_{cb}^*}\right]$$

$$\alpha = \arg\left[-\frac{V_{td} V_{tb}^*}{V_{ud} V_{ub}^*}\right]$$

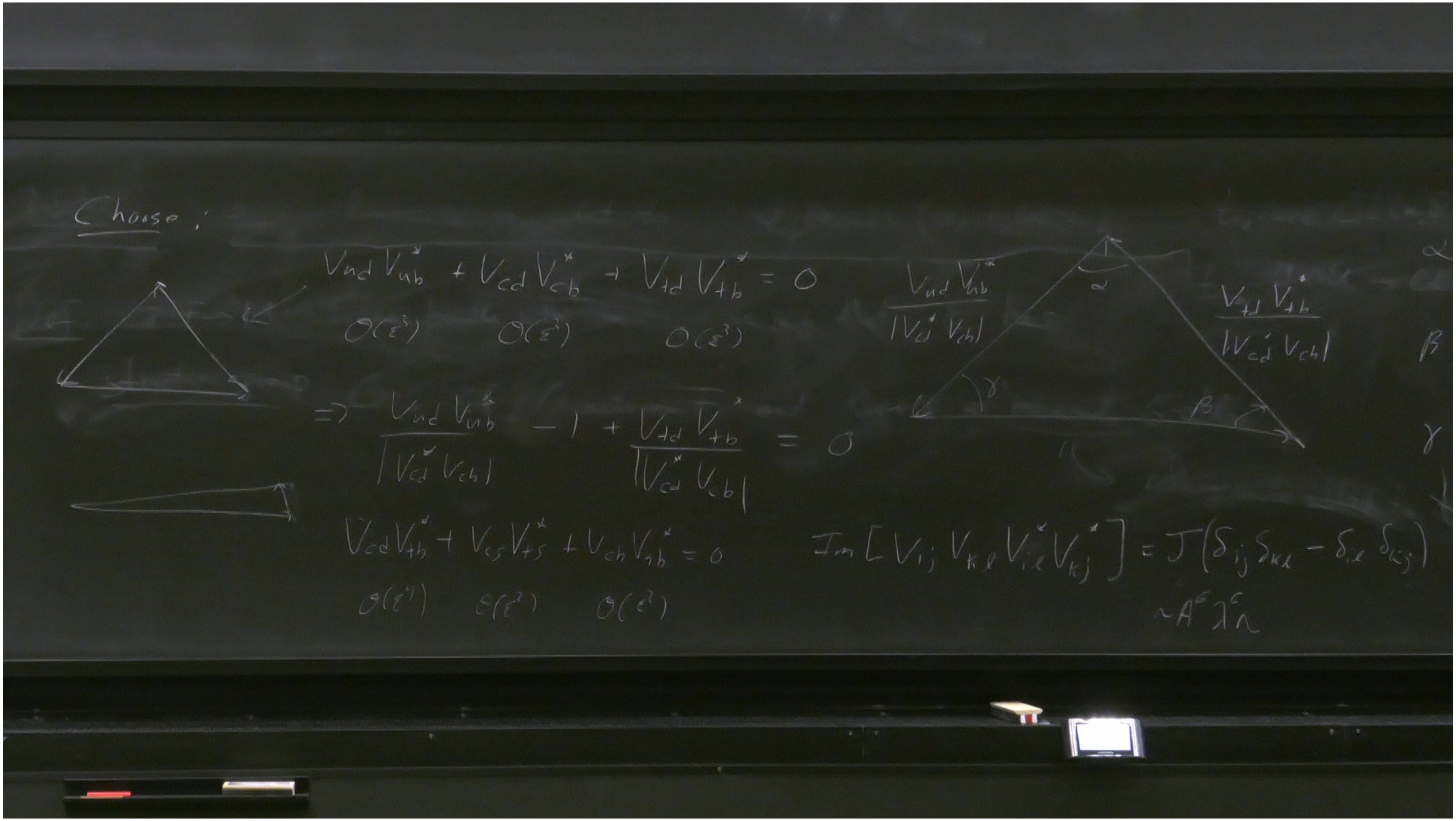
$$\beta = \arg\left[-\frac{V_{cd} V_{cb}^*}{V_{td} V_{tb}^*}\right]$$

$$\gamma = \arg\left[-\frac{V_{cd} V_{cb}^*}{V_{cd} V_{cb}^*}\right]$$

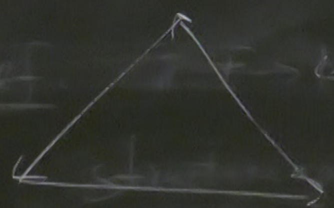
$$\text{Area} = -\frac{1}{2} \operatorname{Im}\left(\frac{V_{ud} V_{ub}^*}{V_{cd} V_{cb}^*}\right)$$

$$= -\frac{1}{2} \operatorname{Im}\left[\frac{V_{ud} V_{cd}^* V_{cb} V_{ub}^*}{|V_{cd} V_{cb}^*|}\right]$$

$$J = \operatorname{Im}\left[V_{ud} V_{cd}^* V_{cb} V_{ub}^*\right]$$

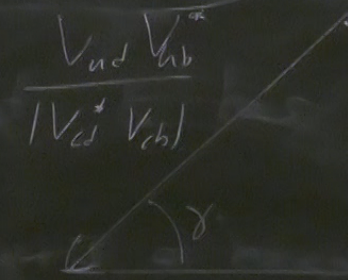

Choose:
$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$
$O(\varepsilon^3)$ $O(\varepsilon^2)$ $O(\varepsilon^3)$
$\Rightarrow \frac{V_{ud}V_{ub}^*}{|V_{cd}^*V_{cb}|} - 1 + \frac{V_{td}V_{tb}^*}{|V_{cd}^*V_{cb}|} = 0$
$V_{cd}V_{tb}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0$
$O(\varepsilon^4)$ $O(\varepsilon^2)$ $O(\varepsilon^2)$
$\frac{V_{ud}V_{ub}^*}{|V_{cd}^*V_{cb}|}$
$\frac{V_{td}V_{tb}^*}{|V_{cd}^*V_{cb}|}$
α β γ 1
$\mathrm{Im}[V_{ij}V_{kl}V_{il}^*V_{kj}^*] = J(\delta_{ij}\delta_{kl} - \delta_{il}\delta_{kj})$
$\sim A^6\lambda^6\eta$

Choose:



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

$$\mathcal{O}(\varepsilon^3) \qquad \mathcal{O}(\varepsilon^2) \qquad \mathcal{O}(\varepsilon^3)$$

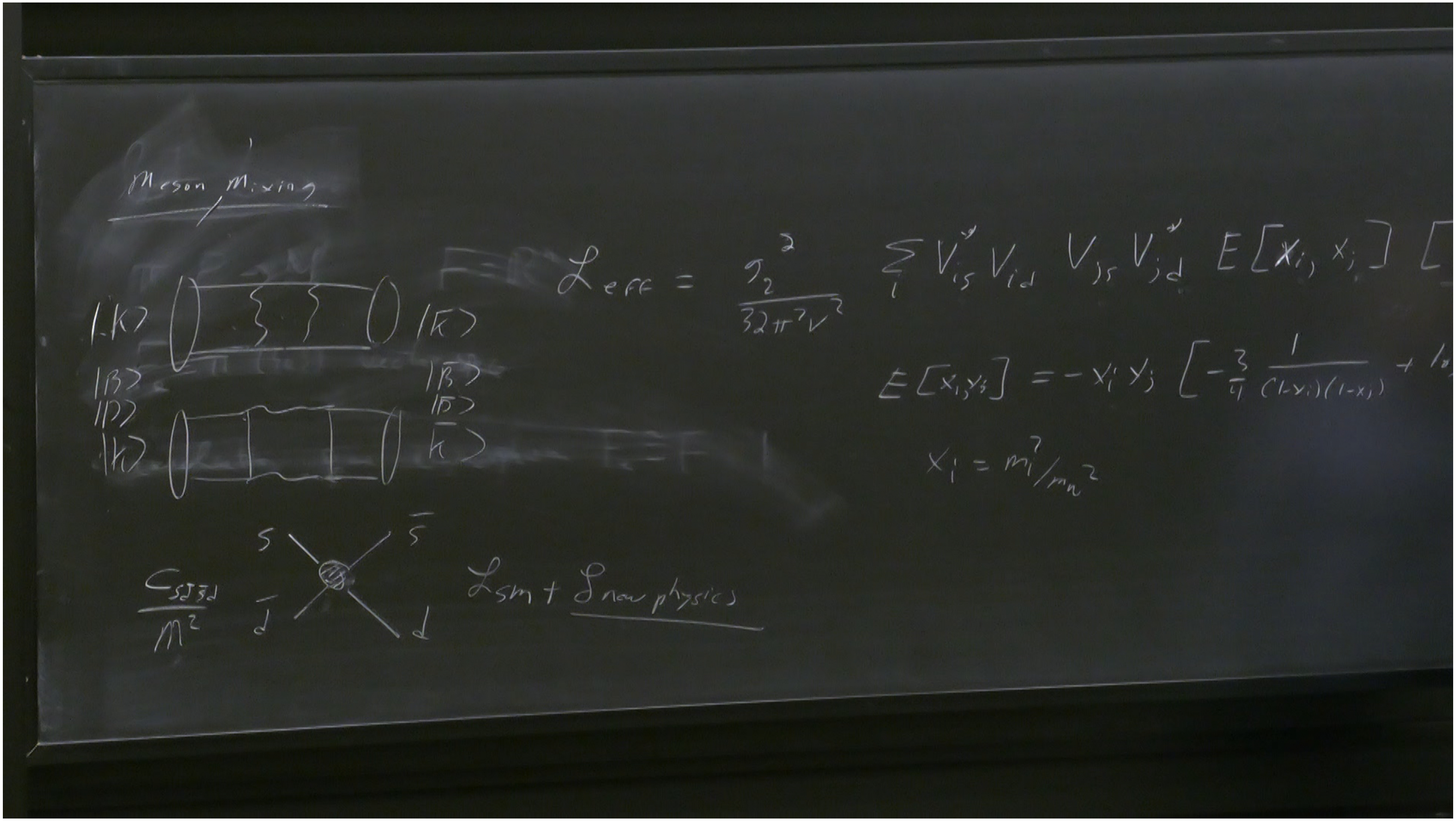


$$\Rightarrow \frac{V_{ud}V_{ub}^*}{|V_{cd}^* V_{cb}|} - 1 + \frac{V_{td}V_{tb}^*}{|V_{cd}^* V_{cb}|} = 0$$

$$V_{cd}V_{tb}^* + V_{cs}V_{ts}^* + V_{cb}V_{tb}^* = 0$$

$$\mathcal{O}(\varepsilon^4) \qquad \mathcal{O}(\varepsilon^2) \qquad \mathcal{O}(\varepsilon^2)$$

$$\mathrm{Im}\left[V_{ij}V_{kl}V_{il}^*V_{k}\ldots\right.$$


Meson Mixing
$|K\rangle$ $|\bar{K}\rangle$
$|B\rangle$ $|\bar{B}\rangle$
$|B\rangle$ $|\bar{B}\rangle$
$|K\rangle$ $|\bar{K}\rangle$
$\mathcal{L}_{eff} = \frac{g_2^2}{32\pi^2 v^2} \sum_i V_{is}^* V_{id} V_{js} V_{jd}^* E[x_i, x_j]$ [
$E[x_i, x_j] = -x_i x_j \left[-\frac{3}{4} \frac{1}{(1-x_i)(1-x_j)} + \right.$
$x_i = m_i^2 / m_W^2$
s $\bar{s}$ $\bar{d}$ d
$\frac{C_{s\bar{d}s\bar{d}}}{M^2}$
$\mathcal{L}_{SM} + \mathcal{L}_{new\ physics}$

$$= \frac{g_2^2}{32\pi^2 v^2} \sum_i V_{is}^* V_{id} V_{js} V_{jd}^* E[x_i, x_j] [\bar{s} \gamma_\mu P_L d][\bar{d} \gamma_\mu P_L s] + h.c.$$

$$E[x_i, y_j] = -x_i y_j \left[-\frac{3}{4} \frac{1}{(1-x_i)(1-x_j)} + \text{log terms} \right]$$

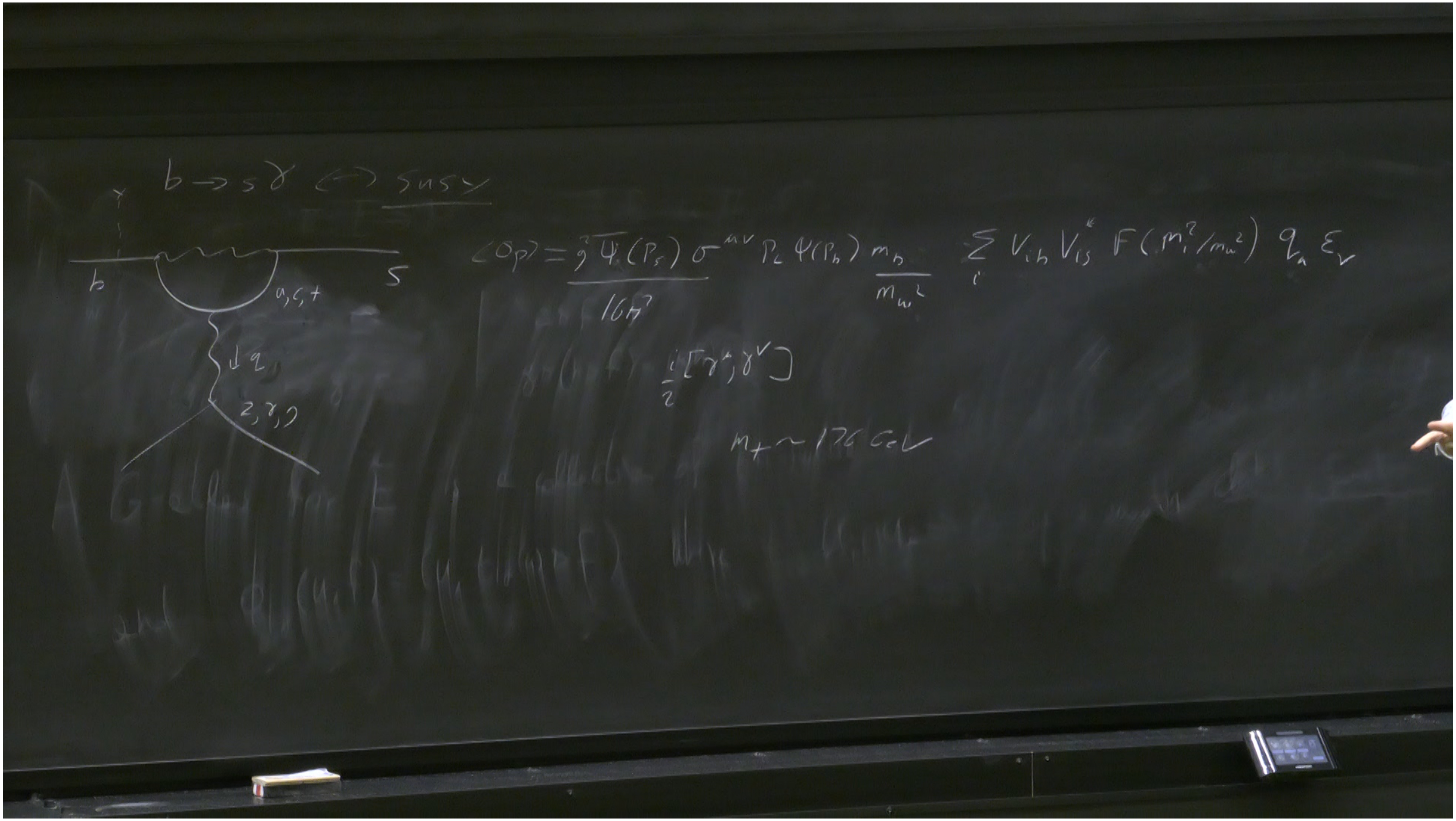
$$x_i = m_i^2 / m_W^2$$

physics

Measured experimentally $= \left[\frac{C_{sd} J_s}{M^2} + \frac{\sum_i V^*_{is} V_{id} \; V_{js} V^*_{jd} \; E[x_i, x_j]}{16\pi^2 v^2} \right] [\;5$

$\Lambda \sim \text{TeV}$, what is $C <$

	$C \sim 1$ Re	Im	Re	Im
Kaon sys	$\Lambda > 9.8 \times 10^2$ GeV	$\Lambda > 1.6 \times 10^4$ GeV	$C < 9 \times 10^{-7}$	$< 3.4 \times 10^{-9}$
B	$> 5.1 \times 10^2$	9.3×10^2	$< 3.3 \times 10^{-6}$	1.0×10^{-6}
D	$> 1.2 \times 10^3$	2.9×10^3	$< 5.6 \times 10^{-7}$	1.0×10^{-7}


b → sγ ↔ SUSY
⟨Op⟩ = g² ψ̄(p_s) σ^μν P_L ψ(p_b) m_b / m_W² Σ_i V_ib V_is* F(m_i²/m_W²) q_μ ε_ν
16π²
i/2 [γ^μ, γ^ν]
m_t ~ 176 GeV
γ
b
s
u, c, t
q
Z, γ, g

Lepton number

Baryon number

$\psi_\ell \Rightarrow e^{i\alpha_\ell}\psi_\ell$ U(1) lepton number

"Global sym"

$\psi_q \Rightarrow e^{i\alpha_q}\psi_q$ U(1) Baryon number

$\to 0$

mass eigen = weak eigenstates

4 parameters $V_{CKM} \to 0$

6 quark masses $\to 0$

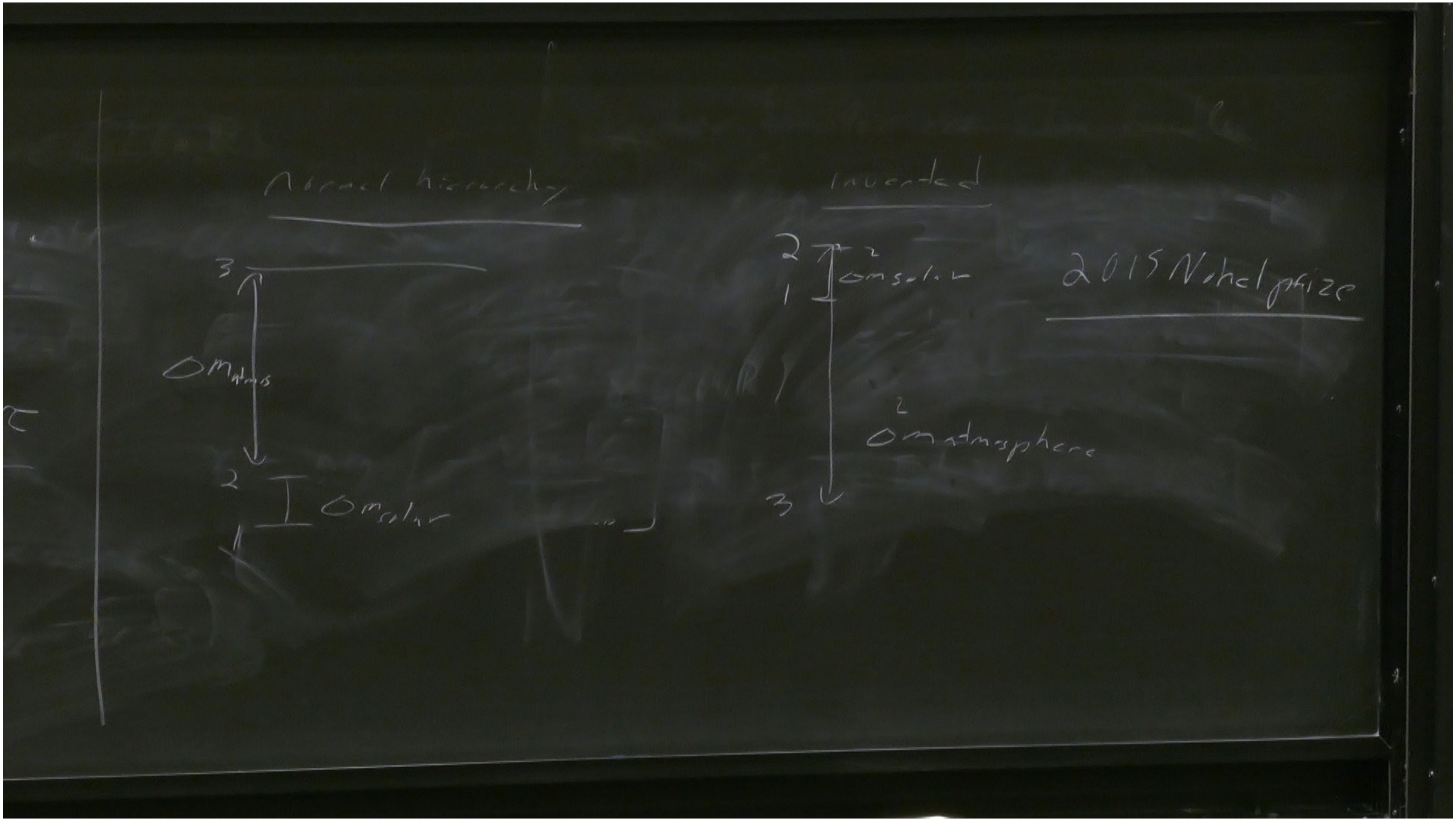
$$\mathcal{L}_{yuk} = -\left[H^\dagger \bar{d}_R Y_d Q_L + \tilde{H}^\dagger \bar{u}_R Y_u q_L + H^\dagger \bar{e}_R Y_e \ell_L + h.c. \right]$$

Solar $\Delta m^2_{12} = 7.37 \times 10^{-5}\, eV^2$

$\hookrightarrow m_e \bar{e} e + m_\mu \bar{\mu} \mu + m_\tau \bar{\tau} \tau$

atmospheric $\Delta m^2_{32} = 2.5 \times 10^{-3}\, eV^2$

$\hookrightarrow m_{\nu_e} = m_{\nu_\mu} = m_{\nu_\tau} = 0$


normal hierarchy
inverted
2015 Nobel prize
Δm^2_{atms}
Δm^2_{solar}
$\Delta m^2_{atmosphere}$

$$\mathcal{L}_{yuk} = -\left[H^\dagger \bar{d}_R Y_d Q_L + \tilde{H}^\dagger \bar{u}_R Y_u q_L + H^\dagger \bar{e}_R Y_e L_L + h.c. \right]$$

Solar $\Delta m^2_{12} = 7.37\times 10^{-5}\,eV^2$

$\hookrightarrow m_e \bar{e} e + m_\mu \bar{\mu}\mu + m_\tau \bar{\tau}\tau$

atmospheric $\Delta m^2_{32} = 2.5\times 10^{-3}\,eV^2$

$\hookrightarrow m_{\nu_e} = m_{\nu_\mu} = m_{\nu_\tau} = 0$

Dirac masses

$$\mathcal{L}_{SM} - \left[\tilde{H}\, \bar{\nu}_R\, Y_\nu\, L_L + h.c. \right]$$

$$U_{PMNS} = U^\dagger(\nu,L)\, U(e,L)$$

Just as for quarks

$$\bar{L}_L\, i \not{D}\, L_L \to \bar{\nu}_L\, \gamma_\mu W^+_\mu\, e_L\, U_{PMNS} + h.c.$$

$$U^\dagger(e,R)\, m_e\, U(e,L) = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

$$U^\dagger(\nu,R)\, m_\nu\, U(\nu,L) = \begin{pmatrix} m_{\nu_1} & & \\ & m_{\nu_2} & \\ & & m_{\nu_3} \end{pmatrix}$$

$$,L) = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}$$

$$\nu,L) = \begin{pmatrix} m_{\nu 1} & & \\ & m_{\nu 2} & \\ & & m_{\nu 3} \end{pmatrix}$$

18 parameters of the SM

$+ \underset{\text{or } 2}{3}\, m_\nu$

+ 4 parameters in <u>U pmns</u>

<u>at least</u>