XII. Novi standardni model

MASE FERMIONA i SM NAKON OTKRIĆA OSCILACIJA NEUTRINA I POTVRDE HIGGSA

- MASE FERMIONA
- MASE NEUTRINA
- ČAROLIJA i ENIGMA HIGGSOVOG SEKTORA

MASE FERMIONA ILI YUKAWINA VEZANJA

Mase fermiona generirane $SU(2) \times U(1)$ simetričnim Yukawinim međudjelovanjem

12 fundamentalnih fermiona u 3 obitelji

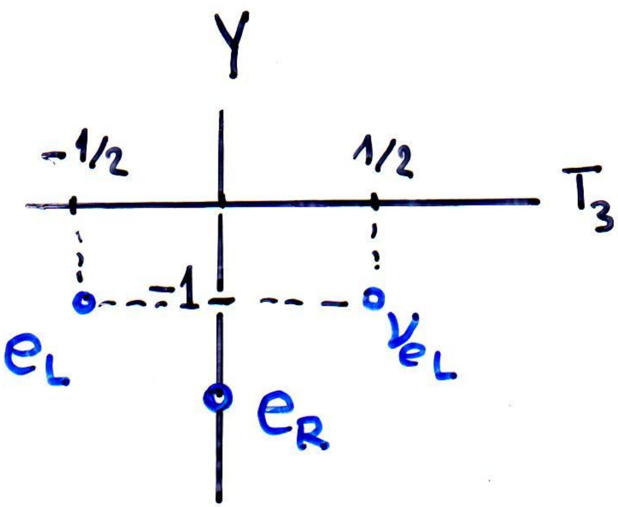
u, d, ν_e, e

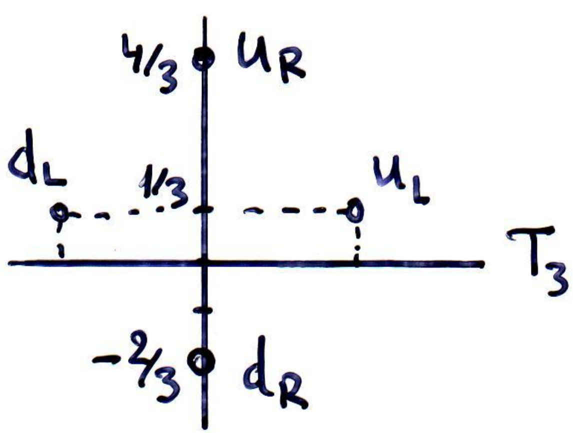
c, s, ν_μ, μ

t, b, ν_τ, τ

15 stanja heliciteta unutar jedne obitelji

Obitelj fermiona realizirana s pet reprezentacija SM-a





	$SU(3)_{boje} \times SU(2) \times U(1)$
$L \equiv \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	$(1, 2, -1)$
e_R	$(1, 1, -2)$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	$(3, 2, 1/3)$
u_R	$(3, 1, 4/3)$
d_R	$(3, 1, -2/3)$

MASE LEPTONA - u unitarnom bažd.

$$m_e = \frac{y_e v}{\sqrt{2}}$$

$$L_L = (\nu_L, e_L)^T$$

$$\Phi = \begin{pmatrix} 0 \\ (v+h)/\sqrt{2} \end{pmatrix}$$

$$\mathcal{L}_{\text{Yukawa}} \supset -\left[y_e \bar{e}_R \Phi^\dagger L_L + y_e^* \bar{L}_L \Phi e_R \right]$$

- Uz umnožak dva dubleta

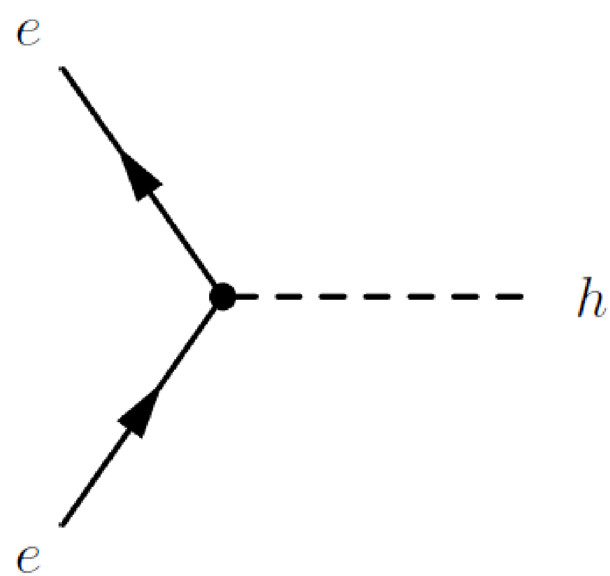
$$\Phi^\dagger L_L = \left(0, \frac{v+h}{\sqrt{2}}\right) \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L = \frac{v+h}{\sqrt{2}} e_L$$

$$\mathcal{L}_{\text{Yukawa}} \supset -y_e \frac{1}{\sqrt{2}} \left[(v+h) \bar{e}_R e_L + (v+h) \bar{e}_L e_R \right]$$

$$= -\frac{y_e}{\sqrt{2}} (v+h) \bar{e} e = -\left(\frac{y_e v}{\sqrt{2}} \right) \bar{e} e - \frac{y_e}{\sqrt{2}} h \bar{e} e$$

Feynmanovo pravilo Yukawinog vrha

$$h\bar{e}e: \quad \frac{-iy_e}{\sqrt{2}} = \frac{-im_e}{v}$$



$$= -i\frac{y_e}{\sqrt{2}} = -i\frac{m_e}{v}$$

- Odražava afinitet fermiona na higgs

$$\frac{y_e}{\sqrt{2}} = \frac{m_e}{v} = \frac{511\ \mathrm{keV}}{246\ \mathrm{GeV}} \simeq 2.1 \times 10^{-6} \qquad \frac{y_\tau}{\sqrt{2}} = \frac{m_\tau}{v} = \frac{1.78\ \mathrm{GeV}}{246\ \mathrm{GeV}} \simeq 7.2 \times 10^{-3}$$

MASE KVARKOVA – donjih i gornjih, za realno Yukawino vezanje

$$m_d = y_d v/\sqrt{2},$$

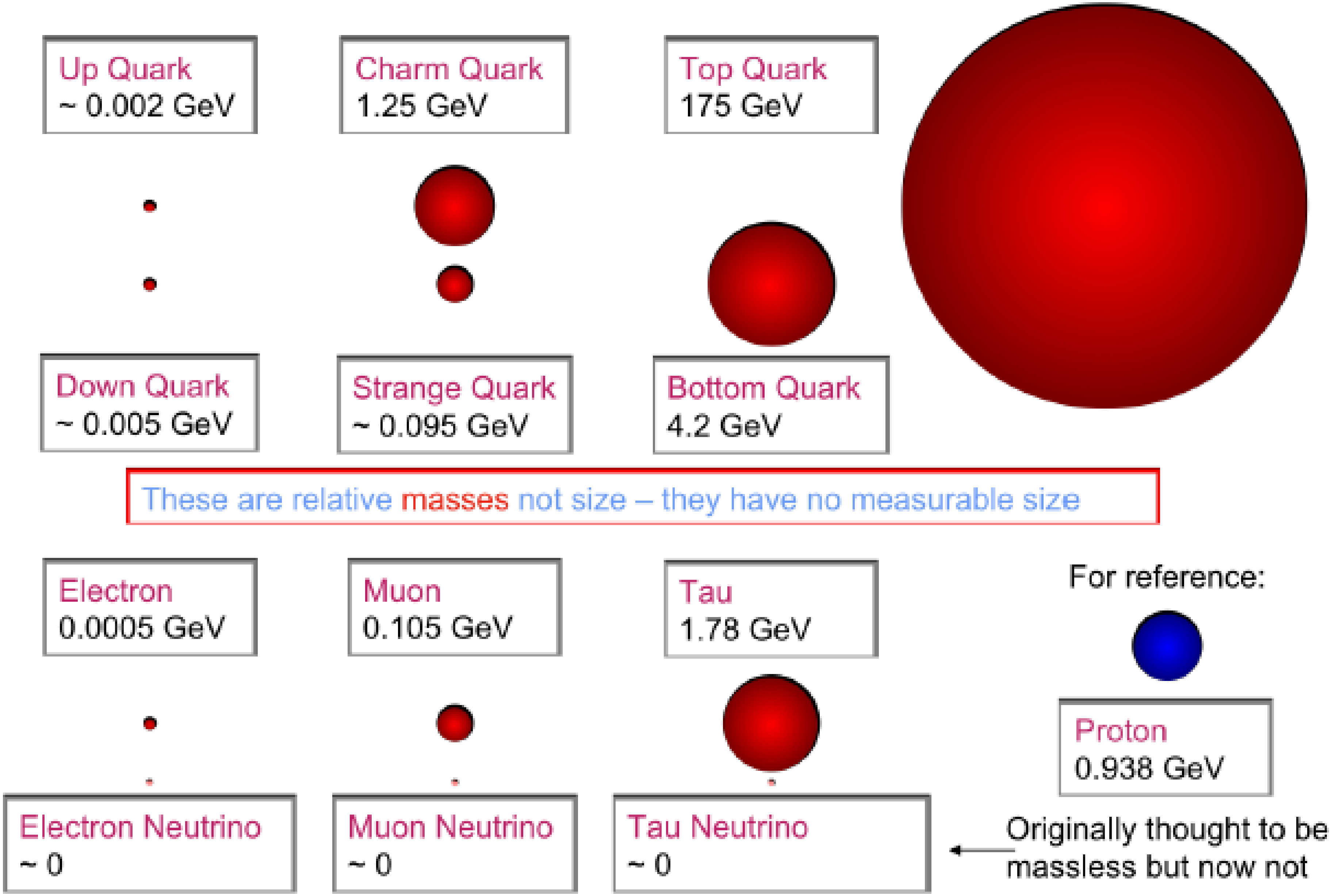
$$m_u = y_u v/\sqrt{2}$$

$$\mathcal{L}_{\text{Yukawa}} \supset -\left[y_d \bar{d}_R \Phi^\dagger Q_L + y_d^* \bar{Q}_L \Phi d_R\right] - \left[y_u \bar{u}_R \tilde{\Phi}^\dagger Q_L + y_u^* \bar{Q}_L \tilde{\Phi} u_R\right]$$

$$\mathcal{L}_{\text{Yukawa}} \supset -\left(\frac{y_d v}{\sqrt{2}}\right)\bar{d}d - \frac{y_d}{\sqrt{2}} h\bar{d}d \qquad \Phi^\dagger Q_L = \left(0, \frac{v+h}{\sqrt{2}}\right)\begin{pmatrix} u_L \\ d_L \end{pmatrix} = \frac{v+h}{\sqrt{2}} d_L$$

- Uz konjugiran dublet $\tilde{\Phi} \equiv i\sigma^2\Phi^* = i\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\begin{pmatrix} \phi^- \\ \phi^{0*} \end{pmatrix} = \begin{pmatrix} \phi^{0*} \\ -\phi^- \end{pmatrix}$

$$\mathcal{L}_{\text{Yukawa}} \supset -\left(\frac{y_u v}{\sqrt{2}}\right)\bar{u}u - \frac{y_u}{\sqrt{2}} h\bar{u}u \qquad \tilde{\Phi}^\dagger Q_L = \left(\frac{v+h}{\sqrt{2}}, 0\right)\begin{pmatrix} u_L \\ d_L \end{pmatrix} = \frac{v+h}{\sqrt{2}} u_L$$


Up Quark
~ 0.002 GeV
Charm Quark
1.25 GeV
Top Quark
175 GeV
Down Quark
~ 0.005 GeV
Strange Quark
~ 0.095 GeV
Bottom Quark
4.2 GeV
These are relative masses not size – they have no measurable size
Electron
0.0005 GeV
Muon
0.105 GeV
Tau
1.78 GeV
For reference:
Proton
0.938 GeV
Electron Neutrino
~ 0
Muon Neutrino
~ 0
Tau Neutrino
~ 0
Originally thought to be massless but now not

Raspad Higgsovog bozona na fermionsko-antiferminski par

- Invarijantna amplituda

$$i\mathcal{M} = \bar{u}_f \left(\frac{-im_f}{v} \right) v_{\bar{f}}$$

čije kvadriranje, sumiranje po polarizacijama (i bojama) i integracija po 2-čestičnom faznom prostoru, daje parcijalnu širinu raspada:

$$\Gamma(h \to f\bar{f}) = \frac{N_c}{8\pi} \frac{m_f^2}{v^2} m_h \left[1 - \frac{4m_f^2}{m_h^2} \right]^{3/2}$$

Miješanje kvarkovskih generacija

$$Q_{Lj}, \quad u_{Rj}, \quad d_{Rj}, \qquad j = 1, 2, 3$$

$$\mathcal{L}^q_{\text{Yukawa}} = -\sum_{i=1}^{3}\sum_{j=1}^{3}\left[y^u_{ij}\bar{u}_{Ri}\tilde{\Phi}^\dagger Q_{Lj} + y^d_{ij}\bar{d}_{Ri}\Phi^\dagger Q_{Lj}\right] + \text{h.c.}$$

$$\mathcal{L}^q_{\text{Yukawa}} \supset -(\bar{u}_1, \bar{u}_2, \bar{u}_3)_R\,\mathcal{M}^u \begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix}_L - (\bar{d}_1, \bar{d}_2, \bar{d}_3)_R\,\mathcal{M}^d \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix}_L + \text{h.c.}$$

- u unit. baždd. kompleksne Yukawine (3x3) matrice vode na matrice masa

$$\mathcal{M}^u_{ij} = \frac{v}{\sqrt{2}}y^u_{ij}, \qquad \mathcal{M}^d_{ij} = \frac{v}{\sqrt{2}}y^d_{ij}$$

BAZA KVARKOVSKIH MASA – dijagonalizacijom biunitarnim transform. $U^{-1} = U^{\dagger}$

$$\begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix}_{L,R} = U_{L,R} \begin{pmatrix} u \\ c \\ t \end{pmatrix}_{L,R} , \qquad \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix}_{L,R} = D_{L,R} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_{L,R}$$

- **Dijagonalizacija masa/Yukawinih matrica**

$$U_R^{-1} \mathcal{M}^u U_L = \begin{pmatrix} m_u & 0 & 0 \\ 0 & m_c & 0 \\ 0 & 0 & m_t \end{pmatrix} , \qquad D_R^{-1} \mathcal{M}^d D_L = \begin{pmatrix} m_d & 0 & 0 \\ 0 & m_s & 0 \\ 0 & 0 & m_b \end{pmatrix}$$

- **Dijagonalna i realna Higgsova vezanja u bazi masa**

$$h\bar{q}q : \quad \frac{-iy_q}{\sqrt{2}} = \frac{-im_q}{v}$$

CKM miješanje u nabijenoj struji & okusno dijagonalna neutralna

$$J_L^{+\mu} = (\bar{u}_1, \bar{u}_2, \bar{u}_3)_L \, \gamma^\mu \begin{pmatrix} d_1 \\ d_2 \\ d_3 \end{pmatrix}_L = (\bar{u}, \bar{c}, \bar{t})_L \, U_L^\dagger \gamma^\mu D_L \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L = (\bar{u}, \bar{c}, \bar{t})_L \, \gamma^\mu V \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L$$

CKM matrica $\quad U_L^\dagger D_L \equiv V$

je unitarna $\quad V^\dagger V = \left(U_L^\dagger D_L\right)^\dagger \left(U_L^\dagger D_L\right) = D_L^\dagger U_L U_L^\dagger D_L = 1$

- Univerzalno vezanje fotona i Z bozona: Q $\quad (T^3 - s_W^2 Q)$
  GIM i granasta odsutnost FCNC

$$(\bar{u}_1, \bar{u}_2, \bar{u}_3)_L \, \gamma^\mu \begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix}_L = (\bar{u}, \bar{c}, \bar{t})_L \, U_L^\dagger \gamma^\mu U_L \begin{pmatrix} u \\ c \\ t \end{pmatrix}_L = (\bar{u}, \bar{c}, \bar{t})_L \, \gamma^\mu \begin{pmatrix} u \\ c \\ t \end{pmatrix}_L$$

Za više obitelji (generacija) -općenito Yukawin lagrangian nije dijagonalan u okusu

$$-\mathcal{L}_Y = G^{(d)}_{ij}\,\bar{Q}'_{L_i}\,\Phi\,D'_{R_j} + G^{(u)}_{ij}\,\bar{Q}'_{L_i}\,\tilde{\Phi}\,U'_{R_j} + h.c.$$

Nakon SSB :

$$-\mathcal{L}_Y = \left(1 + \frac{H(x)}{v}\right) \sum_{i,j=1}^{3} \left\{ (m_U)_{ij}\,\bar{U}'_{L_i} U'_{R_j} + (m_D)_{ij}\,\bar{D}'_{L_i} D'_{R_j} + h.c. \right\}$$

$$U' = \begin{pmatrix} u' \\ c' \\ t' \end{pmatrix} \qquad D' = \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}$$

matrice mase u "baždarnoj" bazi nisu dijagonalne

$$(m_U)_{ij} = -\frac{v}{\sqrt{2}} G^{(u)}_{ij} \quad ; \quad (m_D)_{ij} = -\frac{v}{\sqrt{2}} G^{(d)}_{ij}$$

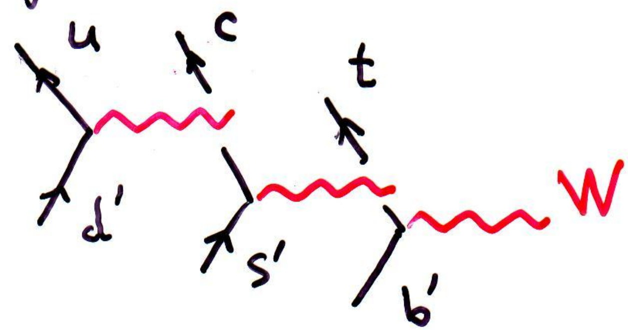
Prijelaz na "fizikalnu" bazu

$$U_{L\,(R)} = V^{U}_{L\,(R)} U'_{L\,(R)} = V^{U}_{L\,(R)} \begin{pmatrix} u' \\ c' \\ t' \end{pmatrix}_{L\,(R)} \quad ; \quad D_{L\,(R)} = V^{D}_{L\,(R)} D'_{L\,(R)} = V^{D}_{L\,(R)} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_{L\,(R)}$$

daje dijagonalne matrice mase

$$\mathcal{L}_M = -\left[\bar{U}_L \, \mathrm{diag}(m_u, m_c, m_t) \, U_R + \bar{D}_L \, \mathrm{diag}(m_d, m_s, m_b) \, D_R + h.c.\right]$$

U fizikalnoj bazi (dobro def. masa) "zakomplicira" se nabijena slaba struja



$$-\mathcal{L}_{cc} = \frac{g}{\sqrt{2}}\left(\bar{U}'_L \gamma^\mu W^\dagger_\mu D'_L + h.c.\right)$$

$$\rightarrow \frac{g}{\sqrt{2}}\left[\bar{U}_L \gamma^\mu \left(V^U_L V^{D\dagger}_L\right) D_L + h.c.\right]$$

volimo oznaku

$$U_L^\dagger D_L \equiv V$$

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$(n \times n)$

$$n^2 - (2n-1) = (n-1)^2 = \frac{n(n-1)}{2} + \frac{(n-1)(n-2)}{2}$$

kutova komplex. faza

Pogodan je odabir slabe baze u kojoj su gornji kvarkovi masena stanja. Izospinski dubleti tada imaju zapis

$$\begin{pmatrix} u \\ d' \end{pmatrix}_L , \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L , \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L ,$$

- gdje je u prostoru generacija

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix}_L = V \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L .$$

"STANDARDNA" PARAMETRIZACIJA – POGODNA ZA POOPĆENJE NA n>3

$$V = R_{23} \times R_{13} \times R_{12}$$

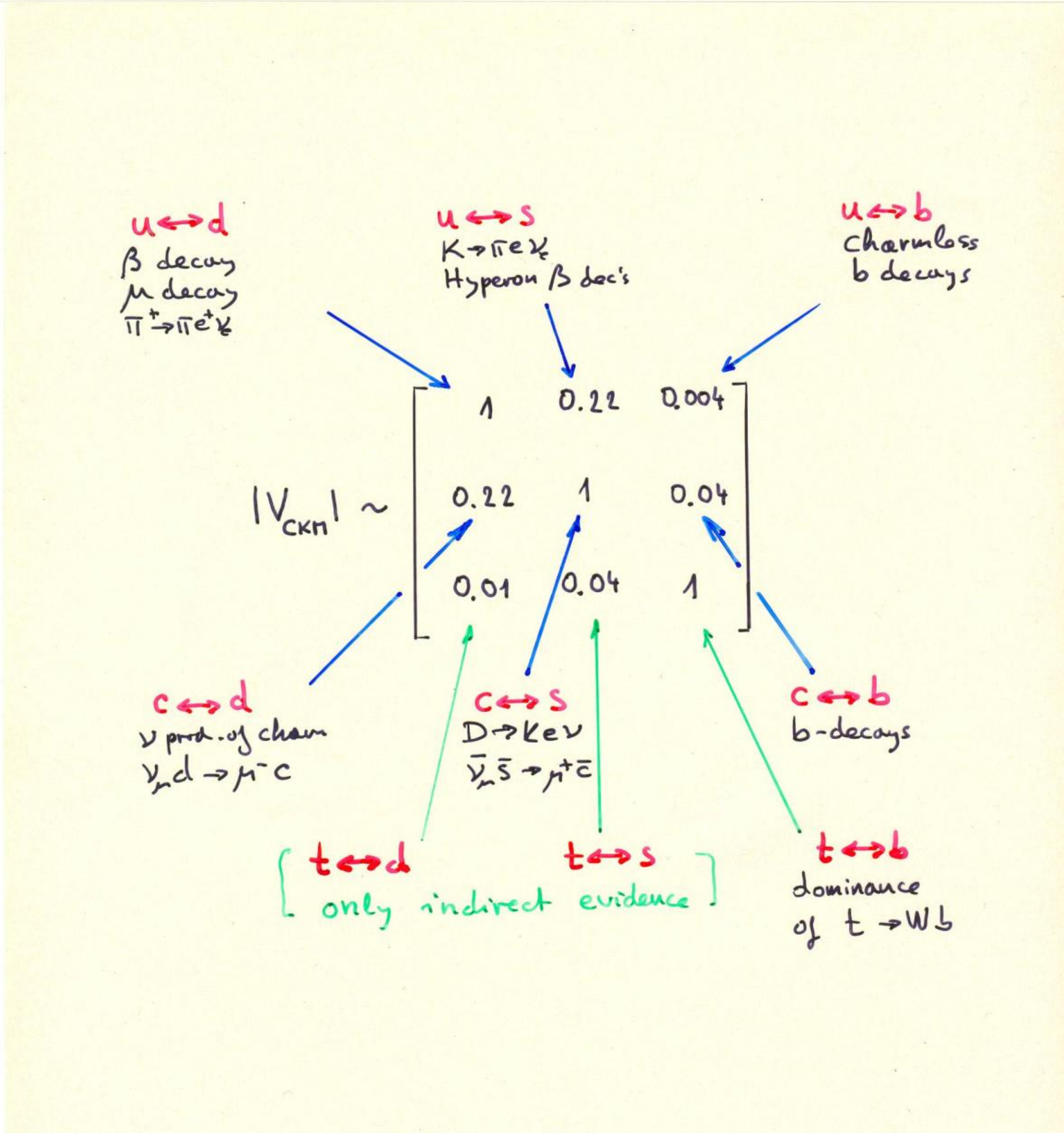
$$R_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, \quad R_{13} = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix}, \quad R_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}$$

"standard parametrization" with $c_{ij} \equiv \cos\vartheta_{ij}$, $s_{ij} \equiv \sin\vartheta_{ij}$, i & j labeling quark families

$$V_{PDG} \simeq \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23} & c_{12}c_{23} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23} & c_{23}c_{13} \end{pmatrix}$$

Wolfenstein's [PRL 51 ('83) 1945] approx. with $\lambda \equiv \sin\Theta_c = 0.221$

POSAO FIZIKE OKUSA



6 ZAHTJEVA UNITARNOSTI:
3 "GORNJA" TROKUTA

$$V_{ud}V_{cd}^* \quad + \quad V_{us}V_{cs}^* \quad + \quad V_{ub}V_{cb}^* \quad = 0$$
$$\sim \lambda \qquad\qquad \sim \lambda \qquad\qquad \sim \lambda^5$$

$$V_{ud}V_{td}^* \quad + \quad V_{us}V_{ts}^* \quad + \quad V_{ub}V_{tb}^* \quad = 0$$
$$\sim \lambda^3 \qquad\qquad \sim \lambda^3 \qquad\qquad \sim \lambda^3$$

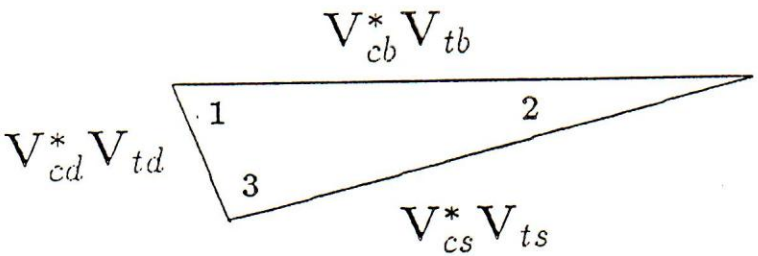
$$V_{cd}V_{td}^* \quad + \quad V_{cs}V_{ts}^* \quad + \quad V_{cb}V_{tb}^* \quad = 0$$
$$\sim \lambda^4 \qquad\qquad \sim \lambda^2 \qquad\qquad \sim \lambda^2$$

& 3 "donja" UNITARNA TROKUTA

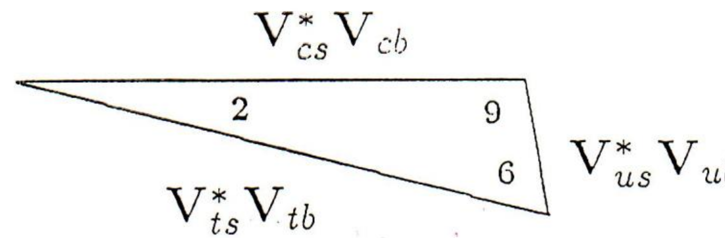
$$V_{ud}^* V_{us} + V_{cd}^* V_{cs} + V_{td}^* V_{ts} = 0$$
$$\sim \lambda \qquad \sim \lambda \qquad \sim \lambda^5$$

$$V_{ud}^* V_{ub} + V_{cd}^* V_{cb} + V_{td}^* V_{tb} = 0$$
$$\sim \lambda^3 \qquad \sim \lambda^3 \qquad \sim \lambda^3$$

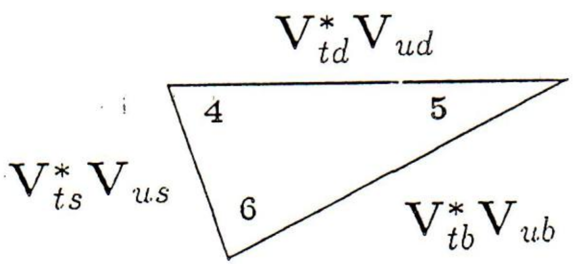
$$V_{us}^* V_{ub} + V_{cs}^* V_{cb} + V_{ts}^* V_{tb} = 0$$
$$\sim \lambda^4 \qquad \sim \lambda^2 \qquad \sim \lambda^2$$



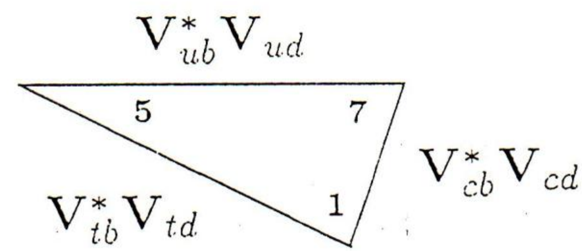
ct $(\triangle_u)$



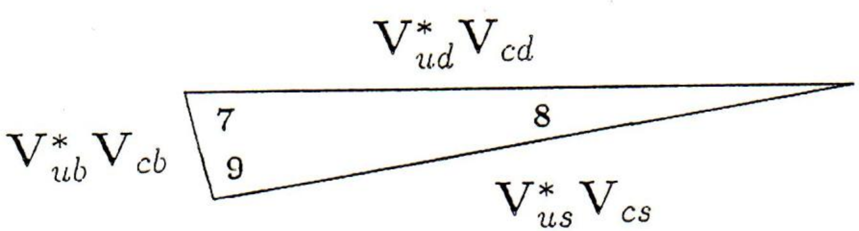
sb $(\triangle_d)$



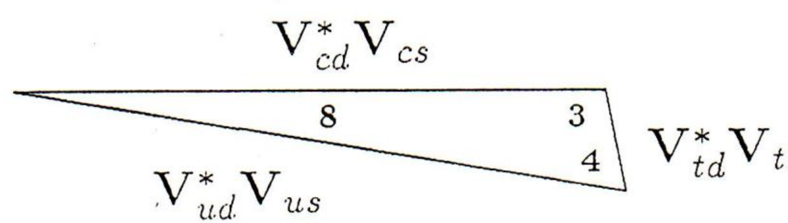
ut $(\triangle_c)$



db $(\triangle_s)$



uc $(\triangle_t)$



ds $(\triangle_b)$

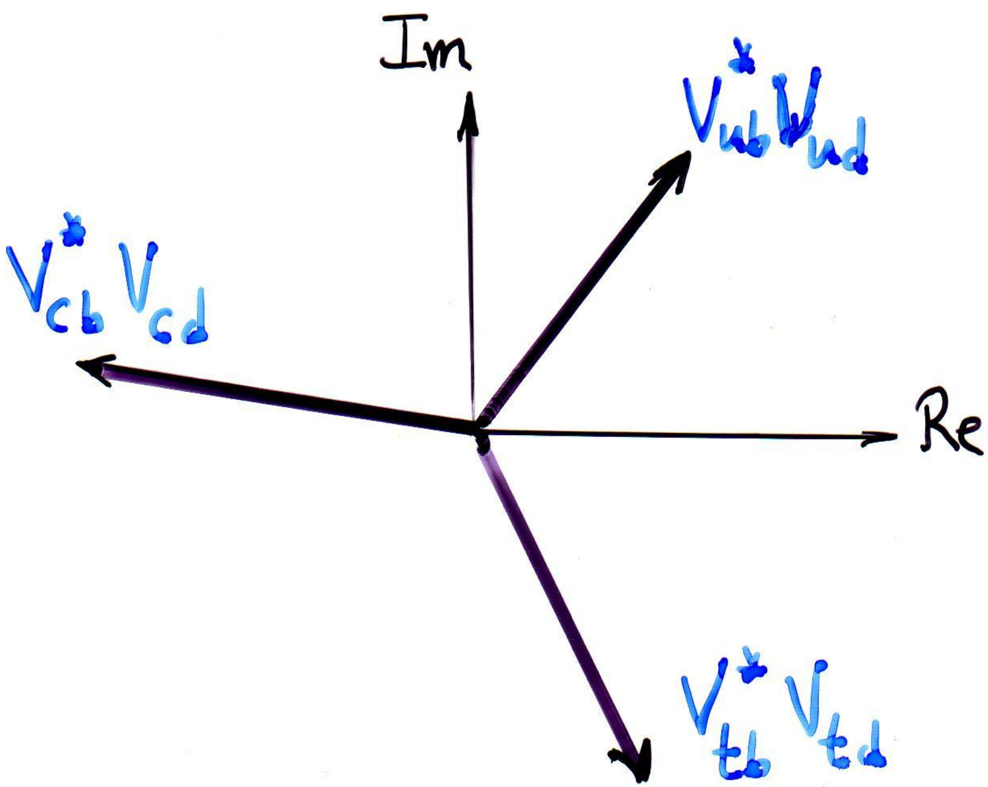
Unitarity

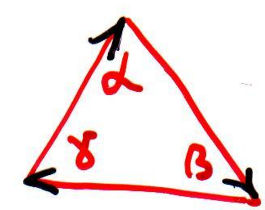
(e.g. (db):

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

$\Rightarrow$ triangle closes

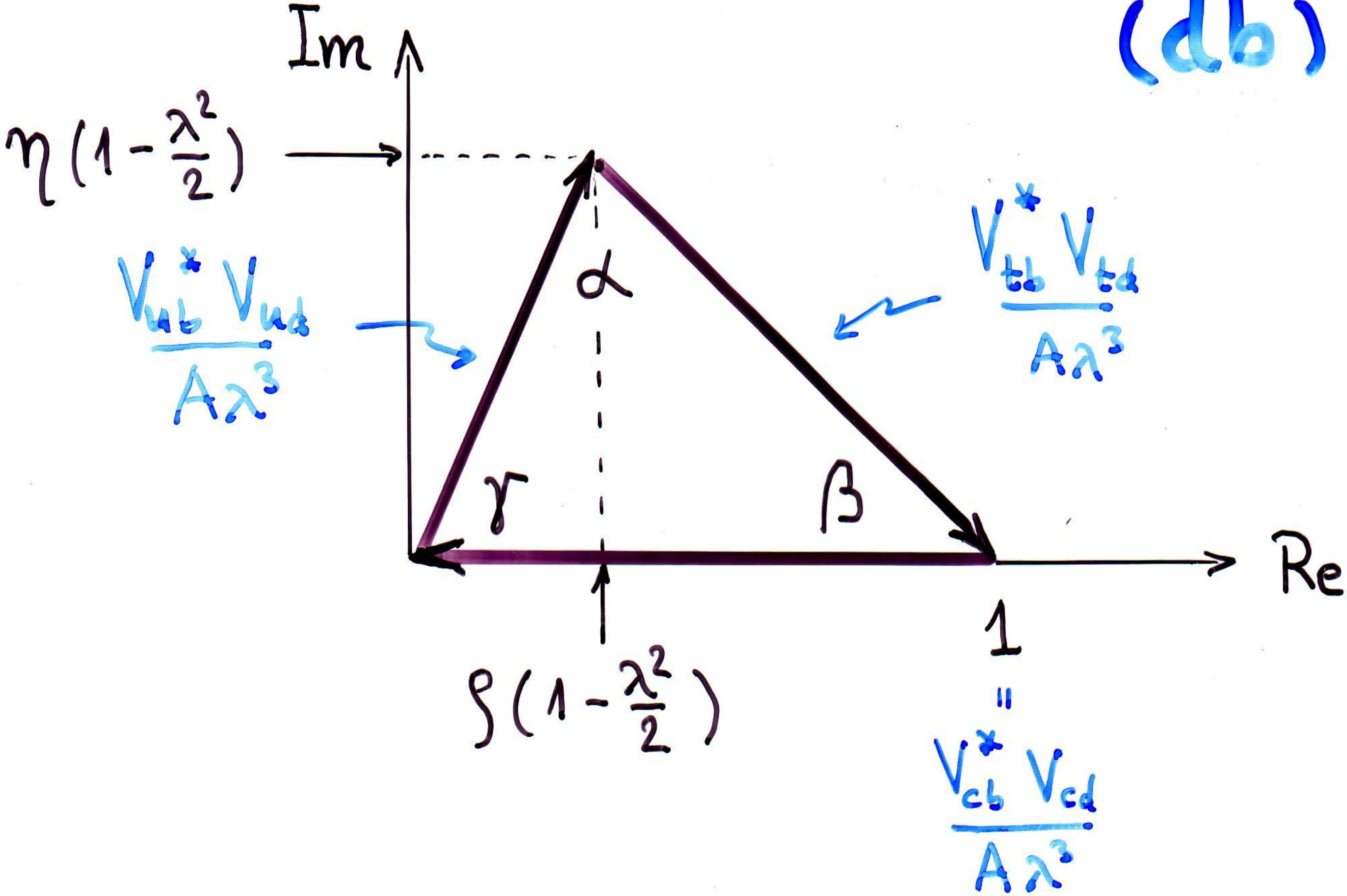
$$\alpha + \beta + \gamma = \pi$$





The two non-squashed unitarity triangles

(db):



Miješanje leptona (Pontecorvo-Maki-Nakagawa-Sakata)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

utvrđeno na temelju pojave
OSCILACIJA NEUTRINA

prva opipljiva naznaka fizike izvan standardnog modela

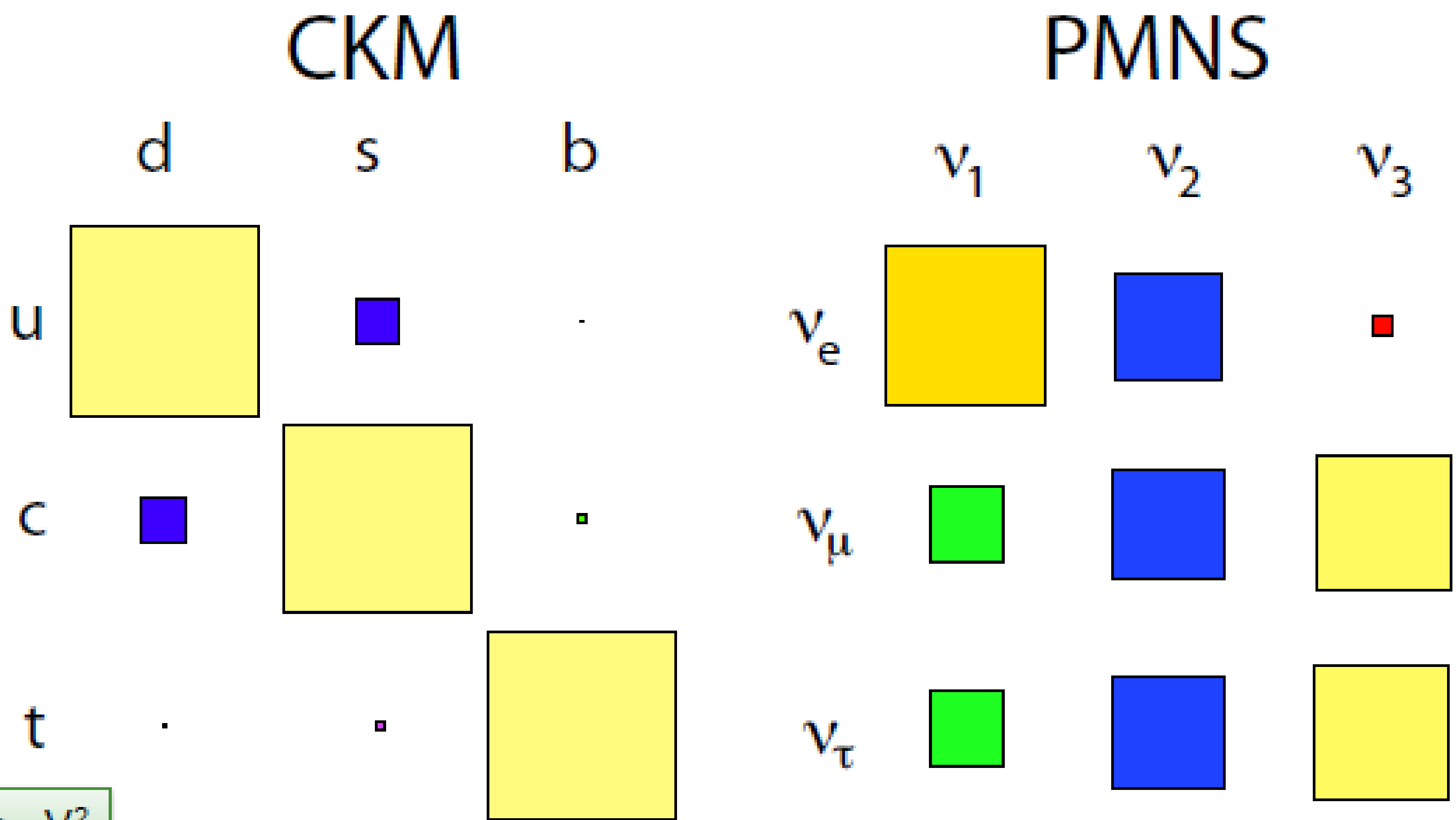
Kao za kvarkove, moguć je odabir slabe baze u kojoj su nabijeni leptoni masena stanja. Izospinski dubleti tada imaju zapis

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L,$$

- tako da PMNS matrica povezuje okusna stanja neutrina s masenim (1,2,3)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L$$

CKM vs. PMNS



Area ~V^2

Why these values? Are the two related? Are they related to masses?

$$|U_{\rm LEP}| = \begin{pmatrix} 0.73-0.89 & 0.44-0.66 & <0.24 \\ 0.23-0.66 & 0.24-0.75 & 0.51-0.87 \\ 0.06-0.57 & 0.40-0.82 & 0.48-0.85 \end{pmatrix}.$$

$$|U_{\rm LEP}| \simeq \begin{pmatrix} \frac{1}{\sqrt{2}}(1+\mathcal{O}(\lambda)) & \frac{1}{\sqrt{2}}(1-\mathcal{O}(\lambda)) & \epsilon \\ -\frac{1}{2}(1-\mathcal{O}(\lambda)+\epsilon) & \frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \\ \frac{1}{2}(1-\mathcal{O}(\lambda)-\epsilon) & -\frac{1}{2}(1+\mathcal{O}(\lambda)-\epsilon) & \frac{1}{\sqrt{2}} \end{pmatrix} \quad \begin{matrix} \lambda \sim 0.2 \\ \epsilon < 0.25 \end{matrix}$$

from quark's

$$|U_{\rm CKM}| \simeq \begin{pmatrix} 1 & \mathcal{O}(\lambda) & \mathcal{O}(\lambda^3) \\ \mathcal{O}(\lambda) & 1 & \mathcal{O}(\lambda^2) \\ \mathcal{O}(\lambda^3) & \mathcal{O}(\lambda^2) & 1 \end{pmatrix} \quad \lambda \sim 0.2$$

★ **To date, results on neutrino oscillations only determine**

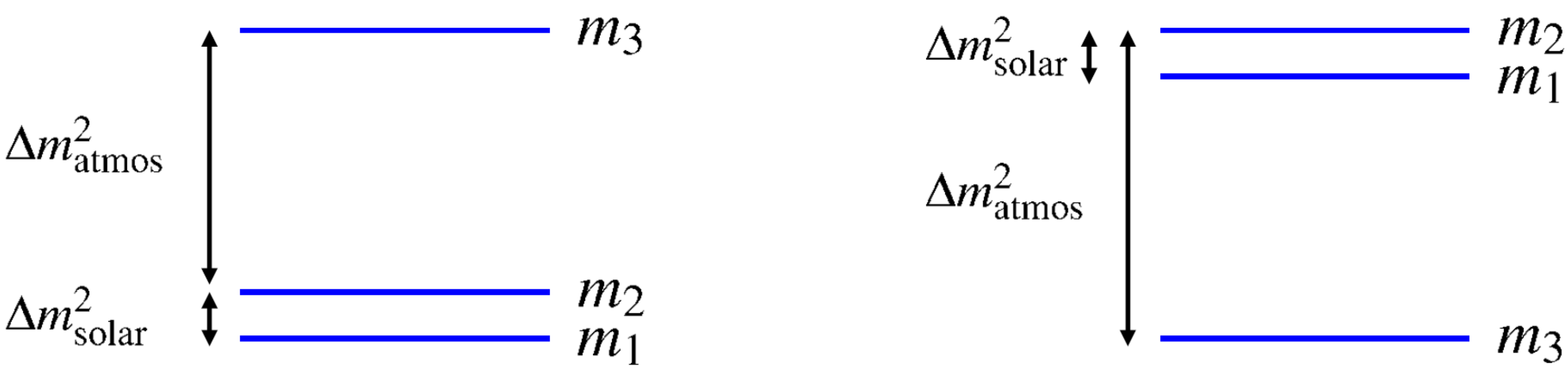
$$|\Delta m^2_{ji}| = |m^2_j - m^2_i|$$

★ **Two distinct and very different mass scales:**

- **Atmospheric neutrino oscillations :** $|\Delta m^2|_{\rm atmos} \sim 2.5 \times 10^{-3}\,{\rm eV}^2$
- **Solar neutrino oscillations:** $|\Delta m^2|_{\rm solar} \sim 8 \times 10^{-5}\,{\rm eV}^2$

•**Two possible assignments of mass hierarchy:**

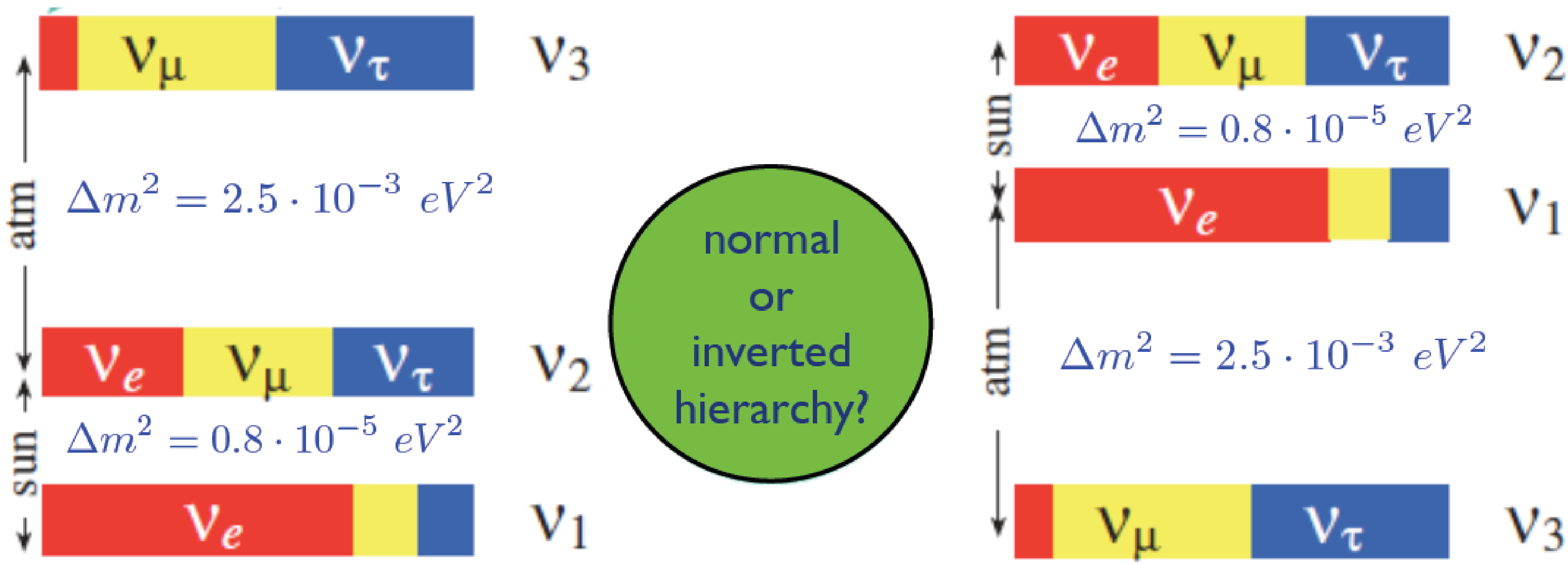
Normal **Inverted**

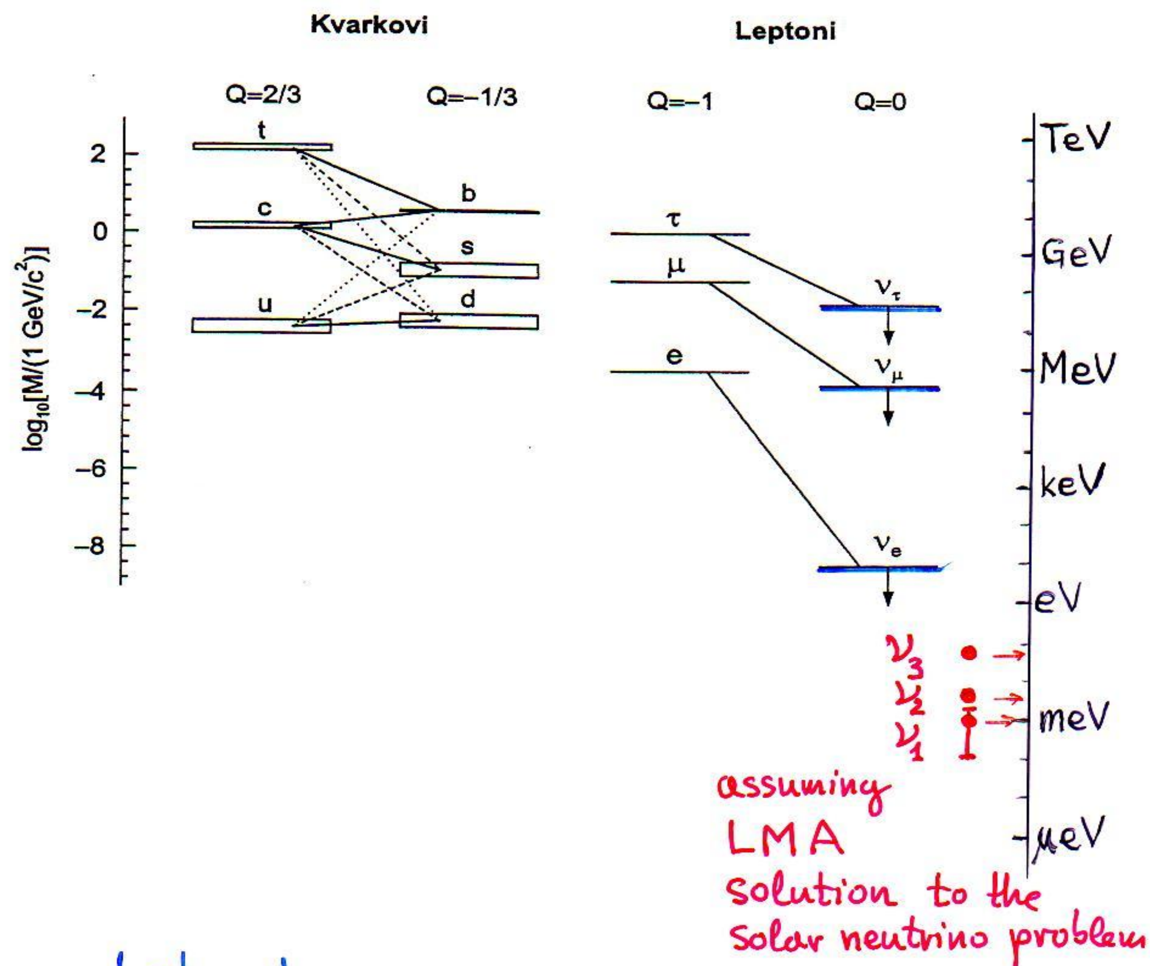


•**In both cases:** $\Delta m^2_{21} \sim 8 \times 10^{-5}\,{\rm eV}^2$ **(solar)**

$$|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \sim 2.5 \times 10^{-3}\,{\rm eV}^2$$ **(atmospheric)**

NORMALNA I INVERZNA HIJERARHIJA MASA NEUTRINA





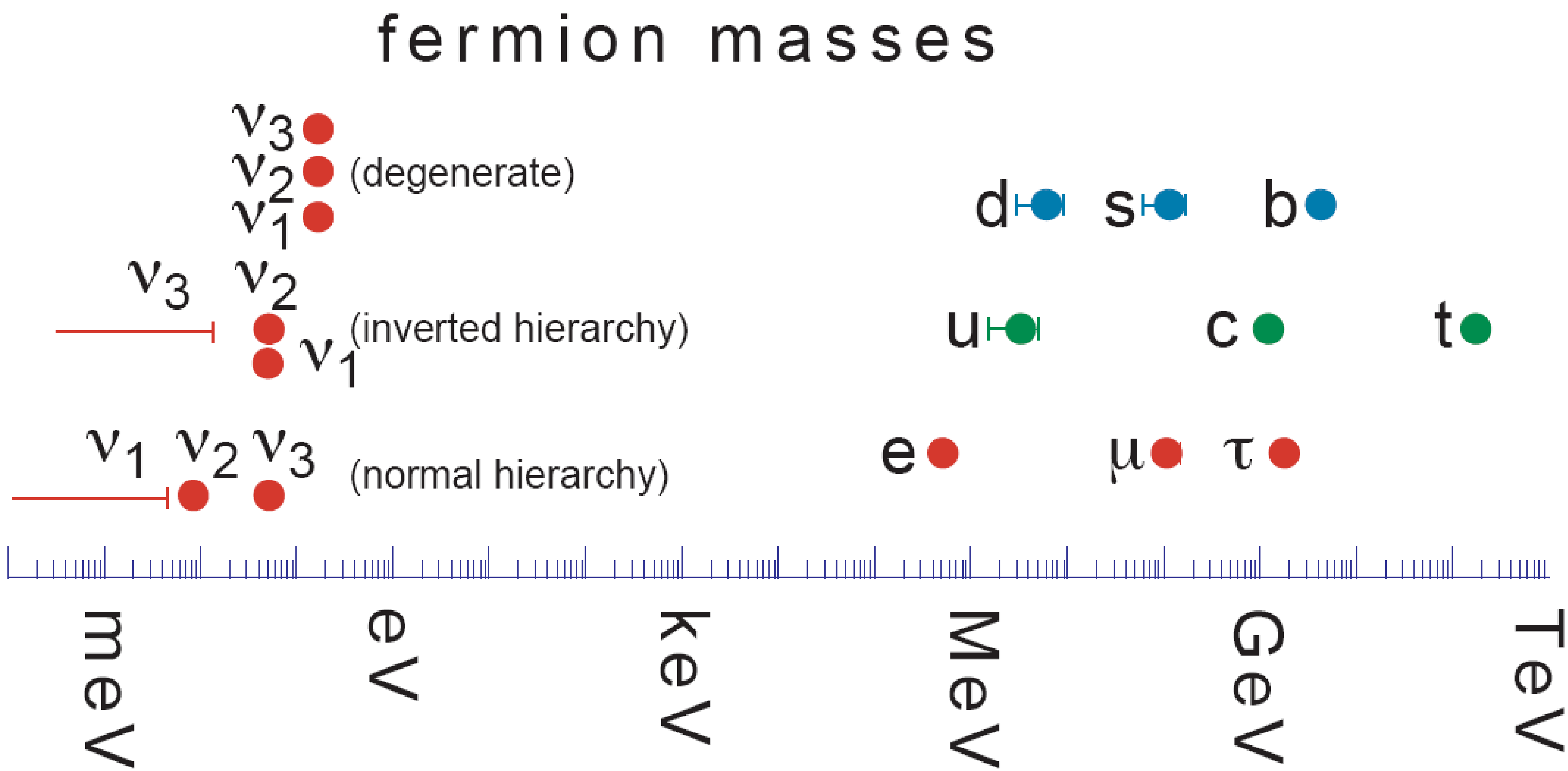
Laboratory mass limits:

$m_{\nu_e} < 5$ eV (^3H β-decay)

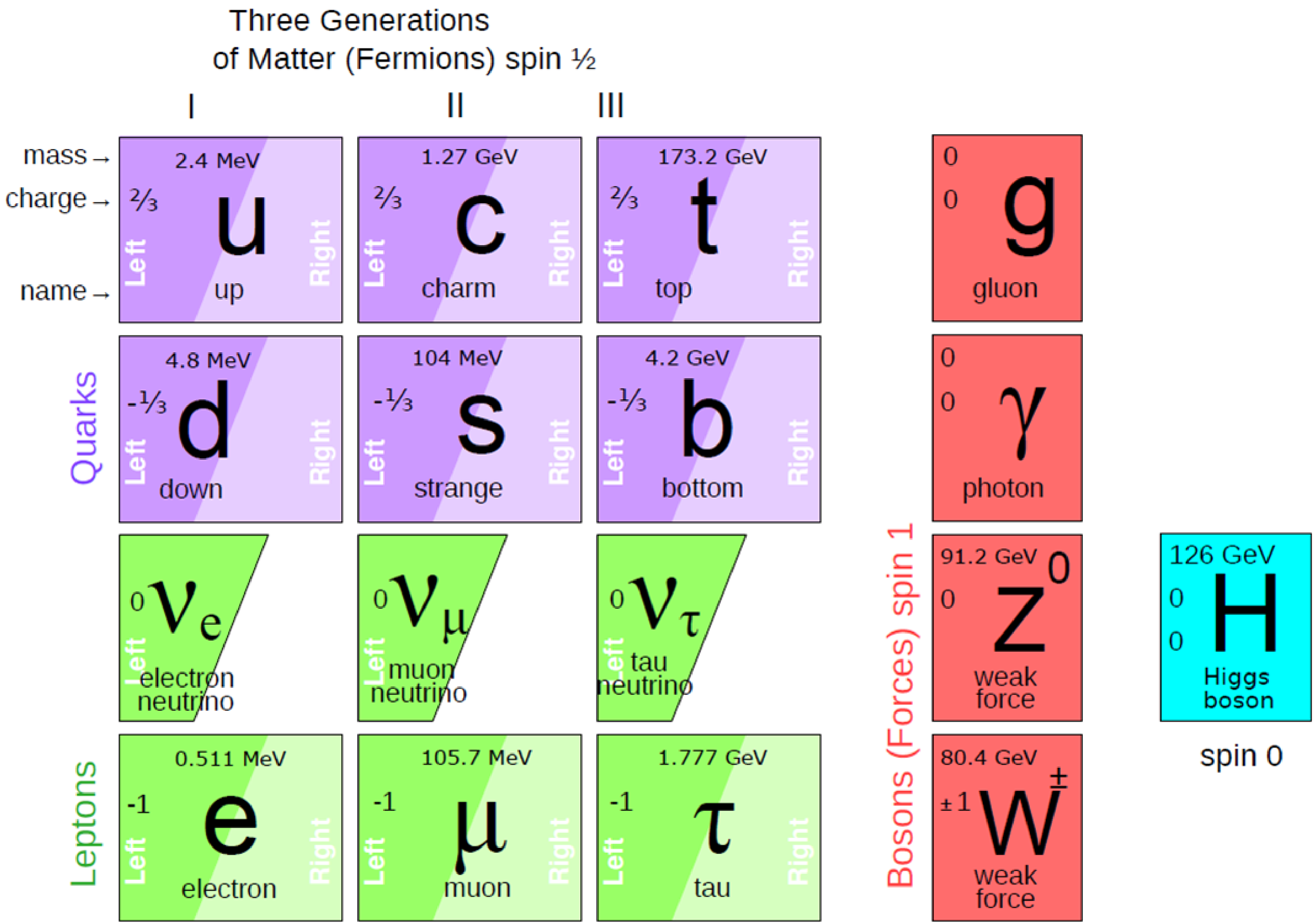
$m_{\nu_\mu} < 0.17$ MeV (PSI)

$m_{\nu_\tau} < 18.2$ MeV (ALEPH)

Neutrinske mase kao opipljivo odstupanje od SM-a Fig.Murayama'08



PERIODIČKA TABLICA SM-a



NAKON OTKRIĆA HIGGSA

3 parametra Higgsovog potencijala

$$V = \text{const.} + m_H^2 |H|^2 + \lambda |H|^4$$

- **Problem kozmološke konstante**
- **Problem prirodnosti higgsa**
- **Problem vakuumske stabilnosti**

Diracove mase neutrina ukoliko postoje i desni neutrini ν_{Ri} $(i = 1,2,3)$

$$\mathcal{L}_{\text{Yukawa}} \supset -y_\nu \bar{\nu}_R \tilde{\Phi}^\dagger L_L + \text{h.c.}$$

$$\mathcal{L}^{\ell}_{\text{Yukawa}} = -\sum_{i=1}^{3}\sum_{j=1}^{3}\left[y^{\nu}_{ij}\bar{\nu}_{R_i}\tilde{\Phi}^\dagger L_{Lj} + y^{\ell}_{ij}\bar{e}_{Ri}\Phi^\dagger L_{Lj}\right] + \text{h.c.}$$

- **PMNS miješanje okusnih i masenih (1,2,3) stanja, pri čemu male mase neutrina**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix}_L = U \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}_L$$

expt.

$$m_\nu \sim 0.1\ \text{eV} \implies \frac{y_\nu}{\sqrt{2}} = \frac{m_\nu}{v} \simeq 4 \times 10^{-13}$$

!!

Weinbergov operator dim 5, generiran česticama nove fizike skale Λ, daje Majoraninu masu neutrina

$$\mathcal{L}_{\mathrm{Majorana}} = -\frac{(\tilde{\Phi}^\dagger L_L)^2}{\Lambda} \qquad m\nu_L\nu_L$$

- nakon SSB, iz korektno napisanog operatora izraženog konjugiranim "L" spinorom koji se Lor-transf. kao "R"

$$\bar{L}_L^c \equiv -L_L^T C, \quad C = -i\gamma^2\gamma^0$$

$$\mathcal{L}_{\mathrm{Majorana}} = -\frac{y_{ij}^{\mathrm{Maj}}}{\Lambda}\bar{L}_{Li}^c\tilde{\Phi}^*\tilde{\Phi}^\dagger L_{Lj} \qquad \Delta L = 2$$

COUNTING the SM's FREE PARAMETERS

3 Gauge couplings

3 g_s, g, g' or $\alpha = \frac{e^2}{4\pi}, \Theta_W, \Lambda_{QCD}$

2 Higgs parameters

2 μ, λ or M_H, λ

9 fermion masses

m_e, m_u, m_d ; m_μ, m_c, m_s ; m_τ, m_t, m_b

4 CKM parameters for 3 generations

$\vartheta_1, \vartheta_2, \vartheta_3$ (mixing angles) & δ (CP-phase)

1 parameter of ~~CP~~ in QCD

Θ_{QCD}

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19 parameters in the minimal case (massless neutrinos)

"OLD SM"

EXTRA PARAMETERS IN THE "NEW SM" νSM

◇ after SNO results

3 neutrino masses

4 MNSP parameters

3 mixing angles & 1 CP-phase

⇒ **7**

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eventually (in the see-saw scenario)

3 Majorana N's masses

2 other angles

⇒ 12 new parameters