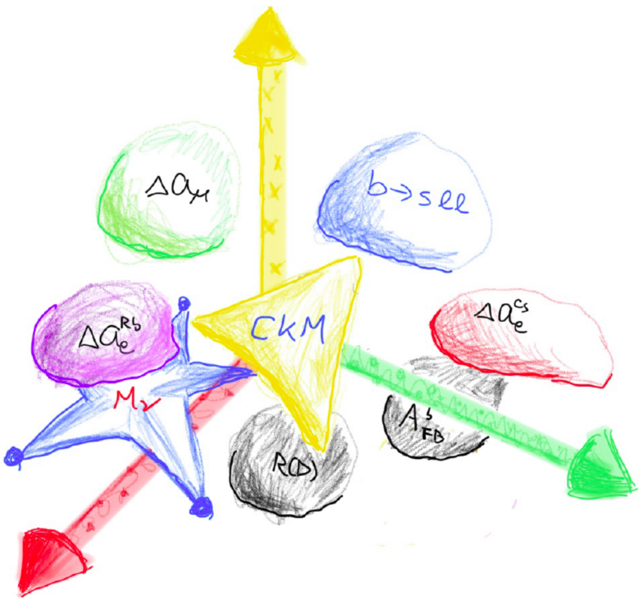
A colorful framework to accommodate the observed anomalies nowadays.



We-Fu Chang
National Tsing Hua University

IOPAS HEP seminar, Jan. 21, 2022

Outlines

- Motivation–Anomalies
- The Model and its solutions
- Constraints and Numerical Study
- Phenomenological consequences
- Origin of the flavor pattern?
- Conclusion

See JHEP 09 (2021) 043 for detailed ref.

1/6. Introduction

Standard Model (SM)

= special relativity + + QM

QFT

particle content +

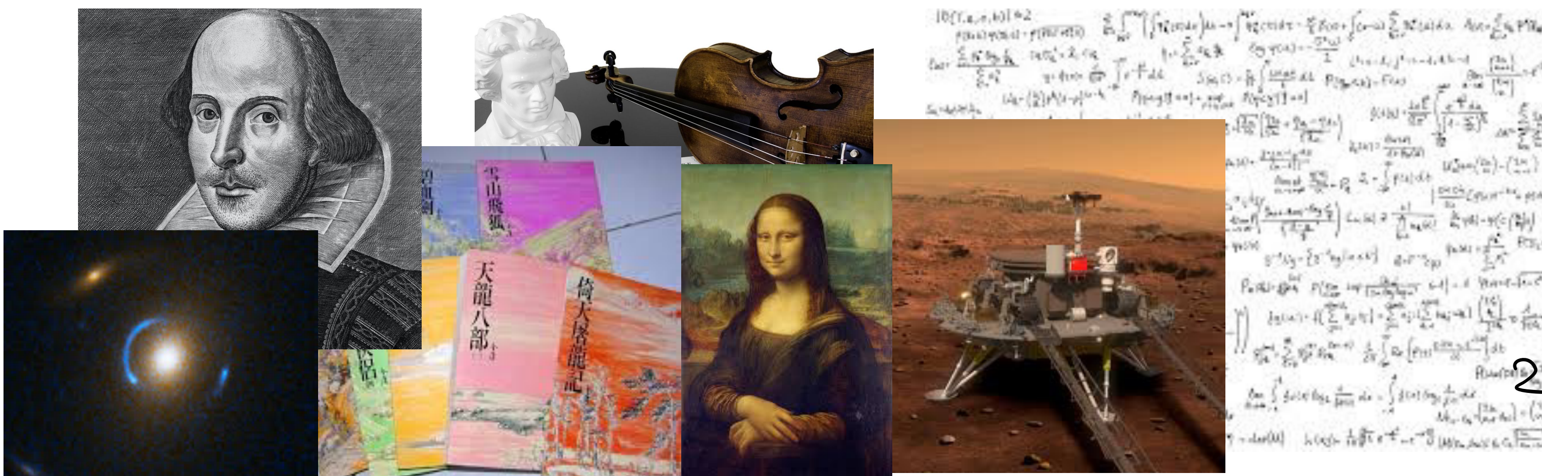
Quarks +Leptons + Higgs

gauge symmetries and breaking

$SU(3)_C \times SU(2)_L \times U(1)_Y$

gluons $W^{\pm}, Z^0, \gamma$

One of the highest intellectual achievements



Standard Model

$\simeq$ special relativity + particle content + gauge symmetries and breaking

+ QM

QFT

Quarks +Leptons
+ Higgs

$SU(3)_C \times SU(2)_L \times U(1)_Y$

gluons $W^{\pm}, Z^0, \gamma$

One of the highest intellectual achievements

Δa_e : electron anomalous magnetic moment

$g = 1$ in classical EM
$g = 2$ by Dirac Eq.
$g = 2(1 + \Delta a)$

$$\Delta a_e^{exp} \simeq 1159652180.73\,(28) \times 10^{-12}$$

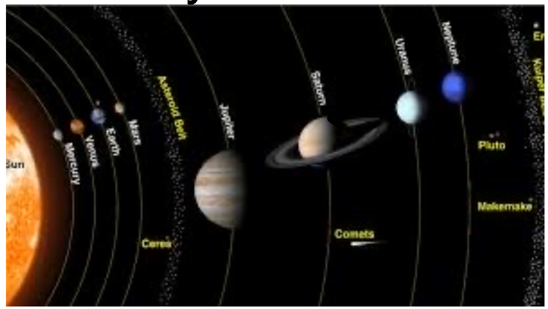
PRA 83, 052122 (2011)

$$\Delta a_e^{th} \simeq 1159652182.032\,(720) \times 10^{-12}$$

PRD 97, 036001 (2018) α(Rb 2016)

1/6. Introduction

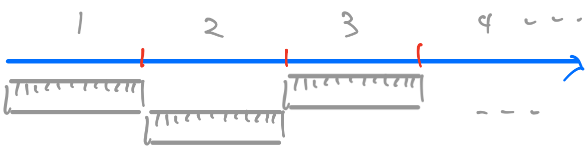
What does 10^{-12} accuracy mean ?

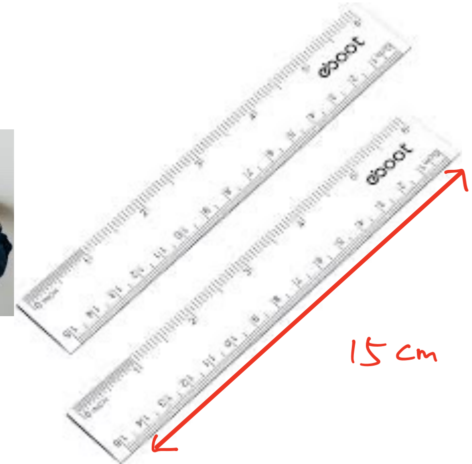


$1AU = 1.5 \times 10^{11} m$

$10^{-12} AU \sim 15 cm$

Say, each measurement per second





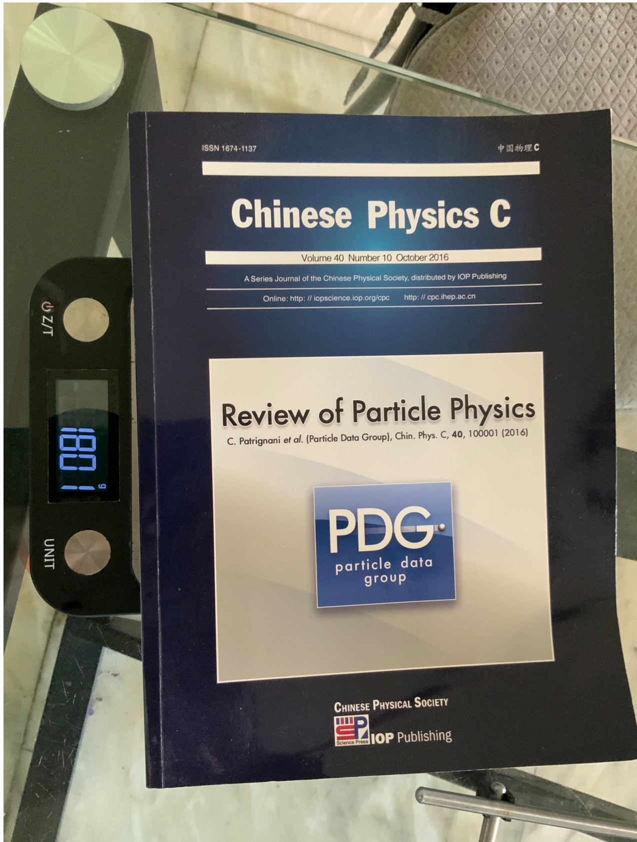
$1y \sim \pi \times 10^7$ sec

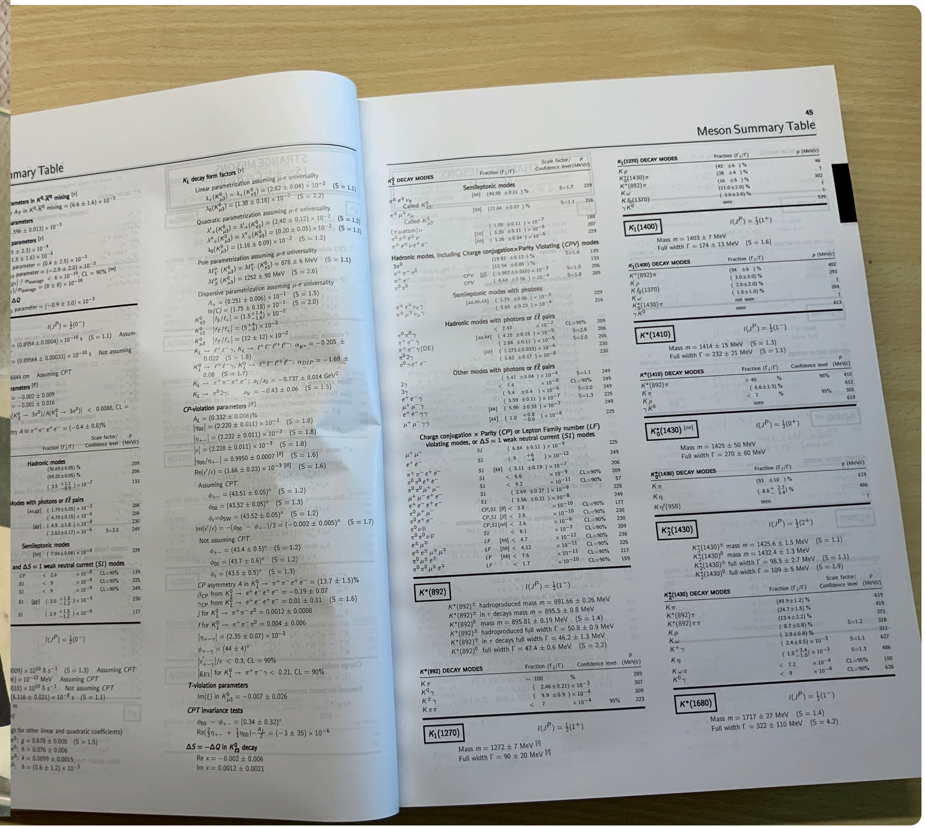
(w/o any rest)

You need to live for $\sim 3 \times 10^4$ years to complete this task, and ONLY 1 measurement mistake is allowed!!

2.5

Not only that





2.5

However, SM is not the end of the story; it is incomplete.

SM=QM+SR

QFT

+particle content

Quarks +Leptons
+ Higgs

+ gauge symmetries
and breaking

$SU(3)_C \times SU(2)_L \times U(1)_Y$

Quantum Gravity?
Dark Energy ?

Neutrino mass?
Antimatter? CPV?
Flavor pattern?

Non-perturbative

$\left\{ \begin{array}{l} \text{confinement} \\ \text{proton mass} \end{array} \right. \Rightarrow \left\{ \begin{array}{l} \text{Models} \\ \text{Lattice} \end{array} \right.$

Dark Matter?

Why 3 generations?

We might need some revolutionary ideas

the main playground for the traditional theoretical particle phys.

Milestones of ν History

from S. Seo
Dark Future Workshop 2021

1988

2002

Pauli: conceptual birth of ν to solve the β decay problem

Lederman et al.: discovery of muon neutrinos

Koshiba et al.: observation of Supernova neutrinos

DONUT: discovery of tau neutrinos

KamLAND: confirmation of solar n osc. using reactor ν (θ_{12})

1930 | 1956 | 1962 | 1968 | 1987 | 1998 | 2000 | 2001 | 2002 | 2012 | ……

Reines & Cowan: discovery of ν (from reactor)

Davis: observation of solar ν

Kajita et al. (Super-K): discovery of atmos. ν osc. (θ_{23})

McDonald et al. (SNO): discovery of solar ν osc. (θ_{12})

Daya Bay, RENO: measurement of the last mixing angle of ν (θ_{13})

1995

2002

2015

2015

4

1/6. Introduction – My   Latest nu-data fit (Oct. 2021)

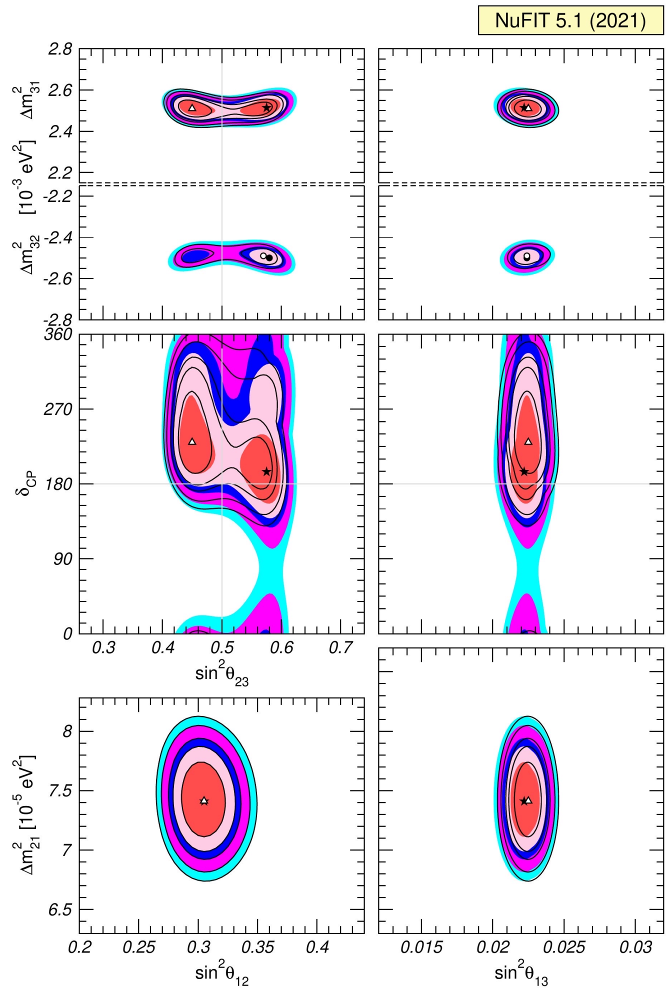
NuFIT 5.1 (2021)

without SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
$\delta_{CP}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$

with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
$\delta_{CP}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$



5

1/6. Introduction

We have kept seeing many ambulances passing by.

6

We have kept seeing many ambulances passing by.

Some wrecked

6

We have kept seeing many ambulances passing by.

Some wrecked . . . .

Some keep going . . .

6

$b \to sll$

- $$R_K^{(*)} = \frac{\Gamma\left(B \to K^{(*)}\mu\mu\right)}{\Gamma\left(B \to K^{(*)}ee\right)}$$

- $$R_K^{SM} = 1.0004^{+0.0008}_{-0.0007}$$

Geng

TABLE I. Key inputs used in

Observable	Value
$\mathrm{BR}(B_s \to \mu^+\mu^-)$	$(2.8^{+0.8}_{-0.7}) \times 10^{-9}$
	$(2.9 \pm 0.7 \pm 0.2) \times 10^{-9}$
	$(3.09^{+0.46+0.15}_{-0.43-0.11}) \times 10^{-9}$
	$(2.842 \pm 0.333) \times 10^{-9}$
	$(3.63 \pm 0.13) \times 10^{-9}$
$R_K[1.1, 6]$	0.846 ± 0.044
$R_K[1, 6]$	1.03 ± 0.28
$R_{K^*}[0.045, 1.1]$	0.660 ± 0.113
$R_{K^*}[1.1, 6]$	0.685 ± 0.122
$R_{K^*}[0.045, 1.1]$	0.52 ± 0.365
$R_{K^*}[1.1, 6]$	0.96 ± 0.463

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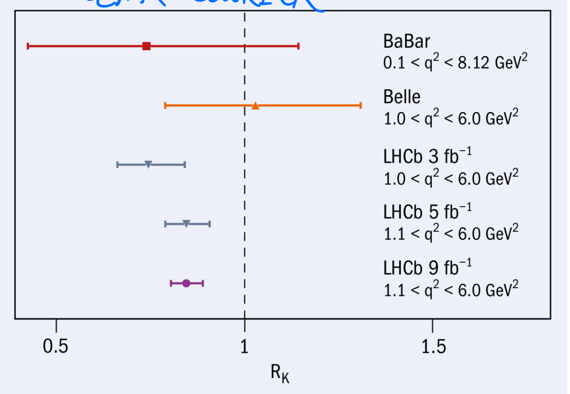


$$\mathcal{H}_{\text{eff}}^{b\to s\mu\mu} = -\frac{G_F}{\sqrt{2}}\widetilde{V}_{tb}\widetilde{V}_{ts}^{*}\frac{\alpha}{\pi}\sum_i \mathcal{C}_i\mathcal{O}_i + H.c.$$

$$\mathcal{O}_9 = \left(\bar{s}\gamma^\alpha \hat{L} b\right)\left(\bar{\mu}\gamma_\alpha\mu\right), \quad \mathcal{O}_{10} = \left(\bar{s}\gamma^\alpha \hat{L} b\right)\left(\bar{\mu}\gamma_\alpha\gamma^5\mu\right),$$
$$\mathcal{O}_9' = \left(\bar{s}\gamma^\alpha \hat{R} b\right)\left(\bar{\mu}\gamma_\alpha\mu\right), \quad \mathcal{O}_{10}' = \left(\bar{s}\gamma^\alpha \hat{R} b\right)\left(\bar{\mu}\gamma_\alpha\gamma^5\mu\right).$$

Global fit:(after Moriond 2021)

Altmannshofer and Stangl , 2103. 13370

$C_9 \simeq -0.73$ or $C_9 \simeq -C_{10} \simeq -0.39$

(theoretically clean modes only $C_{10} \simeq 0.60\,,\ C_9 \simeq -C_{10} \simeq -0.35$)

Geng, Grinstein et al, 2103,12738

$C_9 \simeq -0.82\,,\ C_9 \simeq -C_{10} \simeq -0.40$

$C_{10} \simeq 0.65$

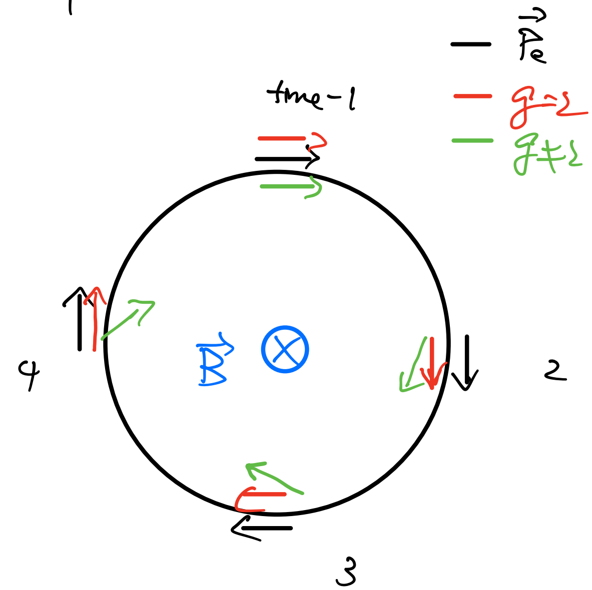
$\vec{\mu}$ (Magnetic moment) $\sim I\vec{A}$ by EM

by Dimension-Analysis $[\vec{\mu}] = \left(\frac{QL^2}{T}\right)_+$ and it is a pseudo-vector $\sim$ spin

$[g] = Q$, $[m] = M$, $[\vec{S}] = \hbar \vec{I} = \frac{ML^2}{T}$

$$\Rightarrow \vec{\mu} \propto \frac{e}{m}\vec{S} \qquad \vec{\mu} = \frac{ge\hbar}{2m}\frac{\vec{\sigma}}{2}$$

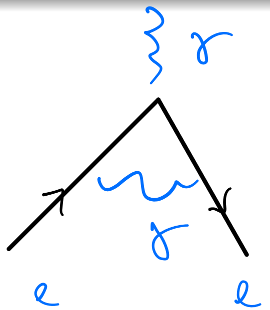
$g = 1$ in classical EM



- Dirac Eq. $\Rightarrow g = 2$ namely (tree level)

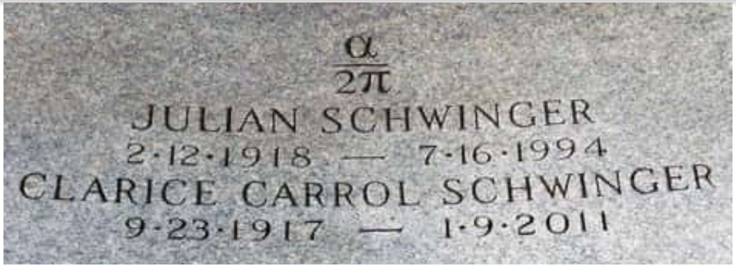
- Quantum correction

$$g = 2\,(1 + \Delta a)$$



$$\Delta a^{(1)} = \frac{\alpha}{2\pi} \sim 1.1617 \times 10^{-3}$$

$$\Delta a^{(2)} \sim O\left(10^{-7}\right)$$



in terms of $\mathcal{L} \supset \bar{L}\sigma^{\mu\nu}F_{\mu\nu}e_R H$ $\Rightarrow$ dim-6 $\frac{1}{\Lambda^2}$

chirality flip $\Rightarrow \propto m_e$ (or M_F in the loop), another normalization $\propto m_e^2$ $(m_e m_F)$

- extremely sensitive to $\alpha \equiv \frac{e^2}{4\pi}$

$$\Delta a_e^{Cs} = a_e^{exp} - a_e^{SM} \simeq (-8.7 \pm 3.6) \times 10^{-13}$$

$\alpha^{-1} = 137.035999046\,(27)$, recoil frequency of ^{133}Cs in matter-wave interferometer

1812.04130

$$\Delta a_e^{Rb} \simeq (+4.8 \pm 3.0) \times 10^{-13}$$ recoil velocity of ^{87}Rb

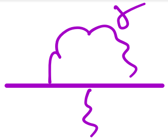
$\alpha^{-1} = 137.035999206\,(11)$

Nature588,61

~5σ difference!!

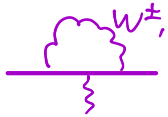
1/6. Introduction

Δa_μ



$\sim \frac{\alpha}{2\pi} \sim O(10^{-3})$

$$a_\mu^{QED} = 116584718.931\,(104) \times 10^{-11}$$

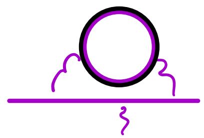


$W^\pm, Z^0, h$

$\sim \frac{G m_\mu^2}{16\pi^2} \sim O(10^{-9})$

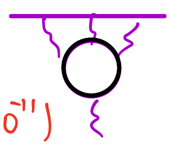
$$a_\mu^{EW} = (153.6 \pm 1.0) \times 10^{-11}$$

a_μ^{HVP} : Largest uncertainty



$\sim \frac{\alpha\, m_\mu^2}{16\pi^2 m_\pi^2} a_\mu^{QED} \sim O(10^{-7})$

$$a_\mu^{HLBL} \times 10^{11} \sim \begin{cases} 90 \pm 20 & \text{pheno} \\ 80 \pm 35 & \text{Lattice} \end{cases}$$



$\sim \frac{\alpha}{16\pi^2} a_\mu^{HVP} \sim O(10^{-11})$

$$\Delta a_\mu \simeq (25.1 \pm 5.9) \times 10^{-10}$$

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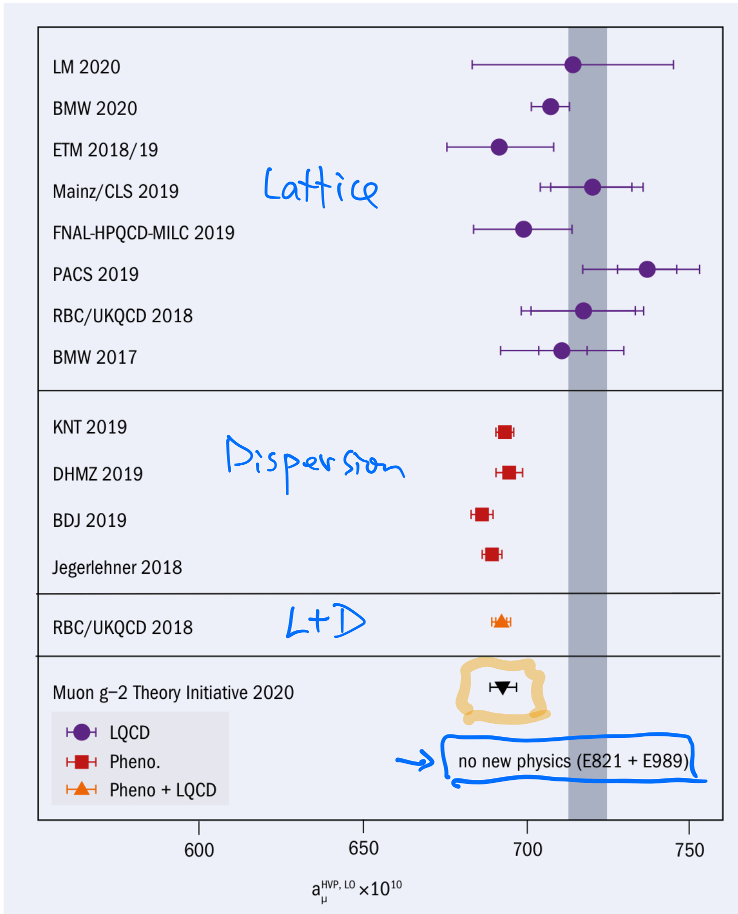

- $$V_{CKM} \equiv V_L^u (V_L^d)^\dagger = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ \sim 0{,}97 & \sim 0{,}23 & \sim 4\times10^{-3} \\ V_{cd} & V_{cs} & V_{cb} \\ \sim -0{,}123 & \sim 0{,}97 & \sim 4\times10^{-2} \\ V_{td} & V_{ts} & V_{tb} \\ \sim 8\times10^{-3} & \sim -4\times10^{-2} & \sim 0{,}99 \end{pmatrix}$$

$|V_{us}| \sim |V_{cd}| \sim |\sin\theta_{Cabbibo}|$

- $V_{CKM} V_{CKM}^\dagger = \mathbb{1}_{3\times3}$

$$\Rightarrow |V_{nd}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

(Since $|V_{ub}|^2 \sim 10^{-5}$, $|V_{ud}|^2 + |V_{us}|^2 \simeq 1$)

- The present PDG value:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0005$$

11

From the 2nd neutrino conference(1974), Pennsylvania,
(As already pointed out by Y Uchida at CLFV2016.)

- The solar neutrino talk by R.K. Ulrik

AIP Conference Proceedings **22**, 259 (1974); doi: 10.1063/1.2947415

The ^{37}Ar production rates for the standard model and the low Z model are 5.6 ± 1.8 SNU and 1.4 ± 0.35 SNU, respectively. Taking Davis's result[1] without run 27 to be 0.2 ± 0.8 SNU I find that the discrepancy between the experiment and the standard model to be 2.7σ and while the discrepancy with the low Z model is 1.4σ.

12

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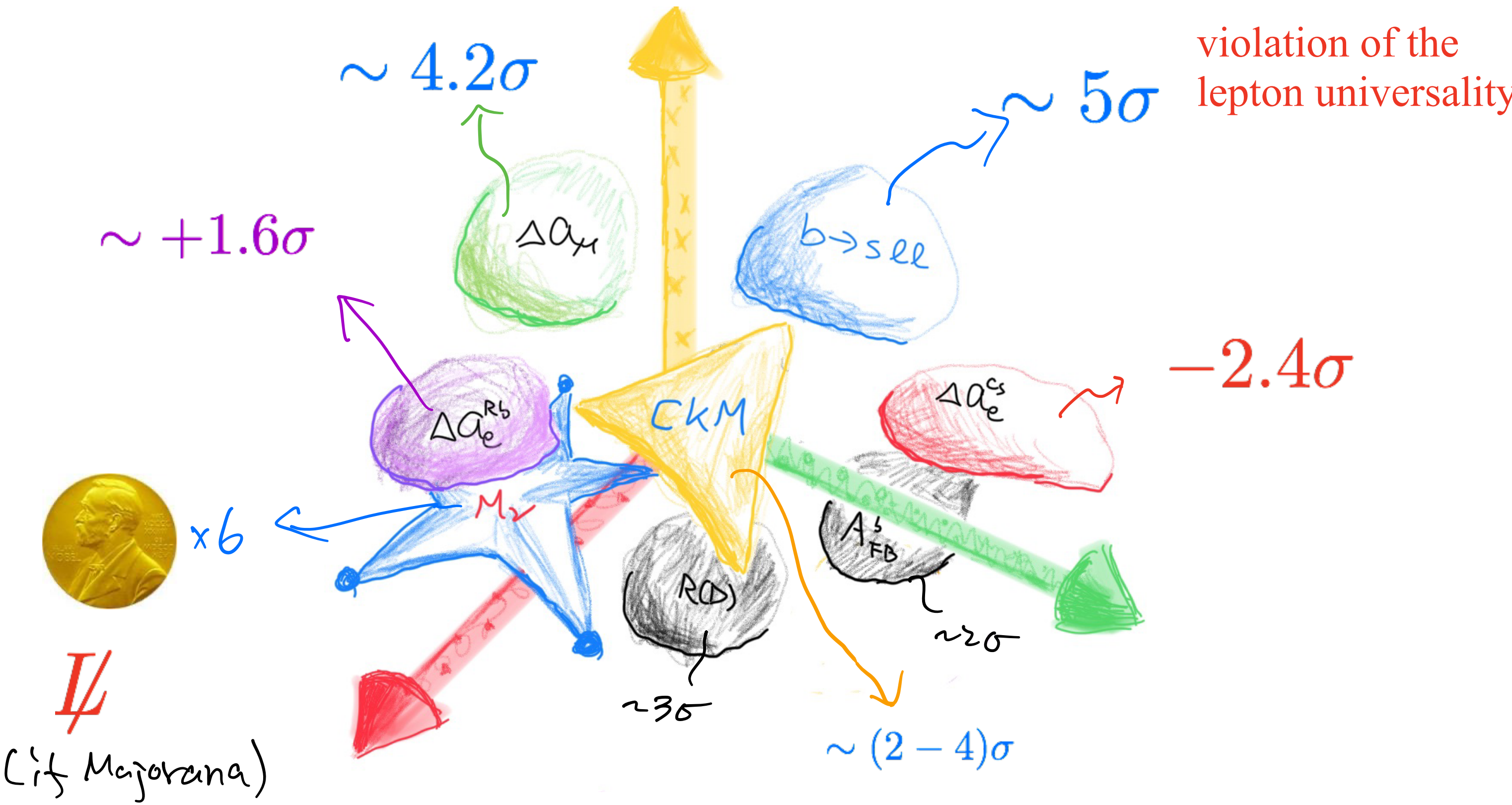
- The Conference Summary by R.P. Feynman

I see no reason to include the solar neutrino problem in here because it is only 1-1/2 standard deviations off of some solar models and the principle is, you don't make a new theory because of 1-1/2 standard deviations.

AIP Conference Proceedings **22**, 299 (1974); doi: 10.1063/1.2947418

By statistics, 1 single anomaly might just be the fluctuation.

But, several/many anomalies is more likely the sign of systematics(New phys).



2/6. The Model and its solutions

① b->s l l : NP connects both lepton/quark sectors

② Neutrino Majorana mass: Lepton# violation

③ CKM leakage : mixing between new fermion and the down (or up) sector.

④ AMM: implies possible heavy fermion in the loop and the new DOFs must be charged.

What can it be?

A straightforward solution:

① b->s l l : NP connects both lepton/quark sectors ⇒ Leptoquark

② Neutrino Majorana mass: Lepton# violation ⇒ LQ triplet + doublet

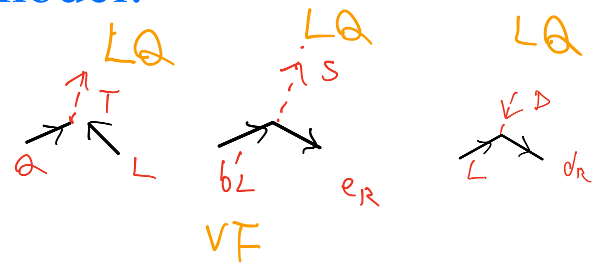
③ CKM leakage : mixing between new fermion and the down (or ~~up~~) sector. ⇒ vector b′

④ AMM: implies possible heavy fermion in the loop ⇒
and the new DOFs must be charged.

⇒ LQ doublet + singlet

- 4 color states are employed in the model:

	New Fermion	New Scalar		
Fields	$b'_{L,R}$	$T=\begin{pmatrix} T^{\frac{2}{3}} \\ T^{-\frac{1}{3}} \\ T^{-\frac{4}{3}} \end{pmatrix}$	$D=\begin{pmatrix} D^{\frac{2}{3}} \\ D^{-\frac{1}{3}} \end{pmatrix}$	$S^{\frac{2}{3}}$
$SU(3)_c$	3	3	3	3
$SU(2)_L$	1	3	2	1
$U(1)_Y$	$-\frac{1}{3}$	$-\frac{1}{3}$	$\frac{1}{6}$	$\frac{2}{3}$
lepton number	0	1	-1	-1
baryon number	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$



- Assuming 2-body decays: $b' \to Wt,\ bZ,\ bH$, $M_{b'} > 1.22$ TeV ATLAS CMS
- LQ mass > 0.5 — 1.6 TeV (see PDG)

take $M_{b'} = 1.5$ TeV, $M_{LQ} \sim 1.0$ TeV as ref. point

- Two possible scalar cubic interactions:

$$\mathcal{L} \supset \mu_3 \left\{H, \tilde{D}\right\} \odot T + \mu_1 \left[H, D\right] S^{-\frac{2}{3}} + H.c.$$

$$= \mu_3 \left[H^+ D^{\frac{1}{3}} T^{-\frac{4}{3}} - \frac{1}{\sqrt{2}} \left(H^0 D^{\frac{1}{3}} - H^+ D^{-\frac{2}{3}}\right) T^{-\frac{1}{3}} - H^0 D^{-\frac{2}{3}} T^{\frac{2}{3}}\right]$$

$$-\mu_1 \frac{1}{\sqrt{2}} \left(H^0 D^{\frac{2}{3}} - H^+ D^{-\frac{1}{3}}\right) S^{-\frac{2}{3}} + H.c.$$

2/6. The Model and its solutions CKM

- Assuming $U(1)_B$, the most general Yukawa is:

$$\mathcal{L} \supset -\widetilde{\lambda}_T T^\dagger \cdot \left\{\bar{L}^c, Q\right\} - \widetilde{\lambda}_D \bar{d}_R \left[L, D\right] - \widetilde{\lambda}'_D \bar{b'}_R \left[L, D\right] - \widetilde{\lambda}_S \bar{e}_R b'_L S^{-\frac{2}{3}} - \widetilde{Y}'_d \bar{Q} b'_R H + H.c.$$

$$= -\widetilde{\lambda}_T \left[\bar{\nu}^c u_L T^{-\frac{2}{3}} + (\bar{\nu}^c d_L + \bar{e}^c u_L) \frac{T^{\frac{1}{3}}}{\sqrt{2}} + \bar{e}^c d_L T^{\frac{4}{3}}\right] - \widetilde{Y}'_d (\bar{u}_L H^+ + \bar{d}_L H^0) b'_R$$

$$- \widetilde{\lambda}_D \frac{\bar{d}_R}{\sqrt{2}} \left(\nu_L D^{-\frac{1}{3}} - e_L D^{\frac{2}{3}}\right) - \widetilde{\lambda}'_D \frac{\bar{b'}_R}{\sqrt{2}} \left(\nu_L D^{-\frac{1}{3}} - e_L D^{\frac{2}{3}}\right) - \widetilde{\lambda}_S \bar{e}_R b'_L S^{-\frac{2}{3}} + H.c.$$

- In addition, new Dirac masses are allowed $\mathcal{L} \supset M_1 \bar{b}'_R b'_L + M_2 \bar{d}_R b'_L + H.c.$

- down-type quark mass matrix becomes 4×4 :

$$\mathcal{L} \supset -(\bar{d_R}, \bar{b'_R}) \mathcal{M}^d \begin{pmatrix} d_L \\ b'_L \end{pmatrix} + H.c.\,, \ \mathcal{M}^d = \begin{pmatrix} \frac{\widetilde{Y}_d v_0}{\sqrt{2}} & M_2 \\ \frac{\widetilde{Y}'_d v_0}{\sqrt{2}} & M_1 \end{pmatrix}$$

- It can be diagonalized by 4X4 biunitary rotation, and the CC int becomes

$$\mathcal{L} \supset \frac{g_2}{\sqrt{2}} (\bar{u}, \bar{c}, \bar{t}) \gamma^\alpha \hat{L} \widetilde{V} \begin{pmatrix} d \\ s \\ b \\ b' \end{pmatrix} W^+_\alpha + H.c. \qquad \widetilde{V} = \begin{pmatrix} \widetilde{V}_{ud} & \widetilde{V}_{us} & \widetilde{V}_{ub} & \widetilde{V}_{ub'} \\ \widetilde{V}_{cd} & \widetilde{V}_{cs} & \widetilde{V}_{cb} & \widetilde{V}_{cb'} \\ \widetilde{V}_{td} & \widetilde{V}_{ts} & \widetilde{V}_{tb} & \widetilde{V}_{tb'} \end{pmatrix}$$

an unpleasant 3×4 matrix !!

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 CKM

- Mathematical trick: consider an auxiliary 4x4 unitary matrix $\tilde{V}_4$

$$\widetilde{V}_4 \equiv \begin{pmatrix} U_L^u & 0 \\ 0 & 1 \end{pmatrix} \cdot (U_L^d)^\dagger = \begin{pmatrix} \widetilde{V}_{ud} & \widetilde{V}_{us} & \widetilde{V}_{ub} & \widetilde{V}_{ub'} \\ \widetilde{V}_{cd} & \widetilde{V}_{cs} & \widetilde{V}_{cb} & \widetilde{V}_{cb'} \\ \widetilde{V}_{td} & \widetilde{V}_{ts} & \widetilde{V}_{tb} & \widetilde{V}_{tb'} \\ (U_L^d)^*_{d4} & (U_L^d)^*_{s4} & (U_L^d)^*_{b4} & (U_L^d)^*_{b'4} \end{pmatrix}$$

- For simplicity, assume NO extra CPV $\Rightarrow$ 3 extra mixings between $\begin{pmatrix} d \\ s \\ b \end{pmatrix}$ - b'

$$(U_L^d)^\dagger = \begin{pmatrix} (U_{L3}^d)^\dagger & 0 \\ 0 & 1 \end{pmatrix} \cdot R_4\,, \quad \text{where} \quad R_4 = \begin{pmatrix} c_1 & 0 & 0 & s_1 \\ -s_1 s_2 & c_2 & 0 & c_1 s_2 \\ -s_1 c_2 s_3 & -s_2 s_3 & c_3 & c_1 c_2 s_3 \\ -s_1 c_2 c_3 & -s_2 c_3 & -s_3 & c_1 c_2 c_3 \end{pmatrix}$$

- Finally, a delightful expression for $\tilde{V}_4$

$$\widetilde{V}_4 = \begin{pmatrix} V_{CKM} & 0 \\ 0 & 1 \end{pmatrix} \cdot R_4$$

And

$$|\widetilde{V}_{ud}|^2 + |\widetilde{V}_{us}|^2 + |\widetilde{V}_{ub}|^2 = 1 - \underbrace{|\widetilde{V}_{ub'}|^2}_{} \leq 1$$

Leakage

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2/6. The Model and its solutions CKM

- From PDG: $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9985 \pm 0.0005$

  and $\widetilde{V}_{ub'} \simeq 0.9740 s_1 + 0.2265 c_1 s_2 + 0.0036 c_1 c_2 s_3 e^{1.196i}$.

  d-b', s-b'

  we have $|s_1 + 0.233 s_2| \simeq 0.039(7)$

  (note: only θ_1, θ_2)

- Other predictions of CKM triangles :

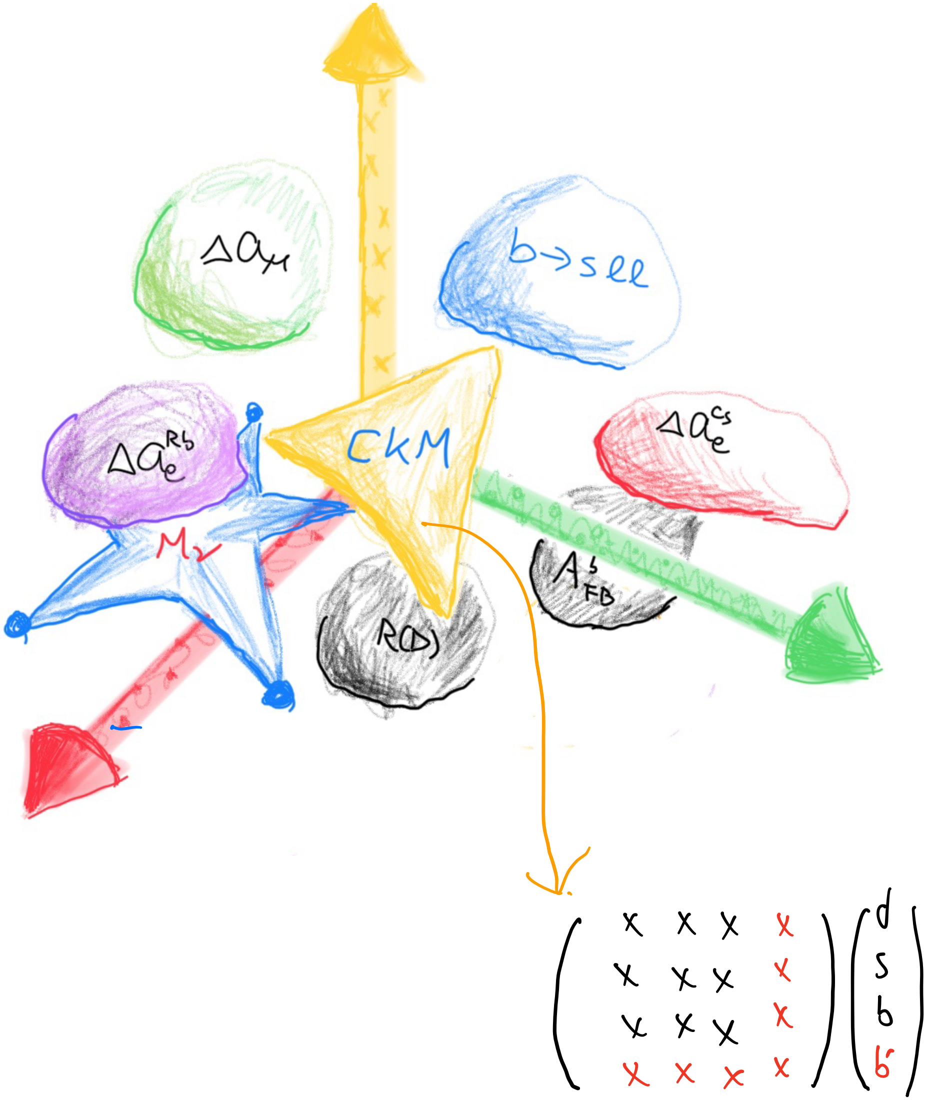
$$\widetilde{V}_{ud}\widetilde{V}^*_{ub} + \widetilde{V}_{cd}\widetilde{V}^*_{cb} + \widetilde{V}_{td}\widetilde{V}^*_{tb} = -(U^d_L)^*_{d4}(U^d_L)_{b4}$$

$$\begin{aligned}
|\widetilde{V}_{cd}|^2 + |\widetilde{V}_{cs}|^2 + |\widetilde{V}_{cb}|^2 &= 1 - |\widetilde{V}_{cb'}|^2 \,, \\
|\widetilde{V}_{td}|^2 + |\widetilde{V}_{ts}|^2 + |\widetilde{V}_{tb}|^2 &= 1 - |\widetilde{V}_{tb'}|^2 \,, \\
|\widetilde{V}_{ud}|^2 + |\widetilde{V}_{cd}|^2 + |\widetilde{V}_{td}|^2 &= 1 - |(U^d_L)_{d4}|^2 \,, \\
|\widetilde{V}_{us}|^2 + |\widetilde{V}_{cs}|^2 + |\widetilde{V}_{ts}|^2 &= 1 - |(U^d_L)_{s4}|^2 \,, \\
|\widetilde{V}_{ub}|^2 + |\widetilde{V}_{cb}|^2 + |\widetilde{V}_{tb}|^2 &= 1 - |(U^d_L)_{b4}|^2 \,,
\end{aligned}$$

- In the mass basis, d_L and u_L have diff LH rotation.

$$\mathcal{L} \supset -(\lambda^T)_{ep}\left(\bar{e}^c_e T^{\frac{4}{3}} + \bar{\nu}^c_e \frac{T^{\frac{1}{3}}}{\sqrt{2}}\right) d_{Lp} - (\lambda^T)_{ep}\, \tilde{V}^\dagger_{pr}\left(\bar{\nu}^c_e T^{-\frac{2}{3}} + \bar{e}^c_e \frac{T^{\frac{1}{3}}}{\sqrt{2}}\right) u_{Lp}$$

using charged lepton/down quark as indices


Δa_μ
b→see
Δa_e^Rb
CKM
Δa_e^Cs
M_ν
A^b_FB
R(D)
d
s
b
b'

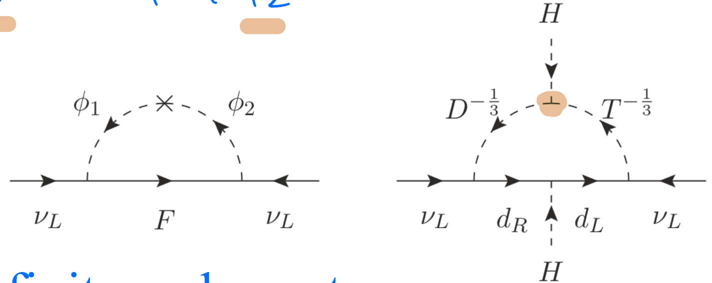
 Neutrino Mass

- Consider a general coupling:

$$\mathcal{L} \supset \lambda_{ij}\bar{F}_j\nu_{Li}\phi_1 + \kappa_{ij}\bar{F}_j\nu_i^c\phi_2 + H.c.$$

L-#: -1 +1 0 -1 -1 +2

$\not{L}$ if ϕ_1 and ϕ_2 mix.



- The 1-loop result is finite and exact:

$$M_{ij}^{\nu} = \sum_k \frac{N_c^F m_k}{16\pi^2} s_\alpha c_\alpha (\kappa_{ik}\lambda_{jk} + \kappa_{jk}\lambda_{ik}) \left[\frac{m_h^2}{m_h^2 - m_k^2} \ln \frac{m_h^2}{m_k^2} - \frac{m_l^2}{m_l^2 - m_k^2} \ln \frac{m_l^2}{m_k^2} \right]$$

α: the mixing angle between ϕ_1 & ϕ_2

- In this model $\phi_{1,2} \sim D, T$, mixing $\propto \mu_3$

$$M_{ij}^{\nu} \simeq \sum_{k=d,s,b,b'} \frac{3m_k}{32\pi^2} (\lambda_{ik}^T\lambda_{jk}^D + \lambda_{jk}^T\lambda_{ik}^D) \frac{\mu_3 v_0}{M_D^2 - M_T^2} \ln \frac{M_T^2}{M_D^2}$$

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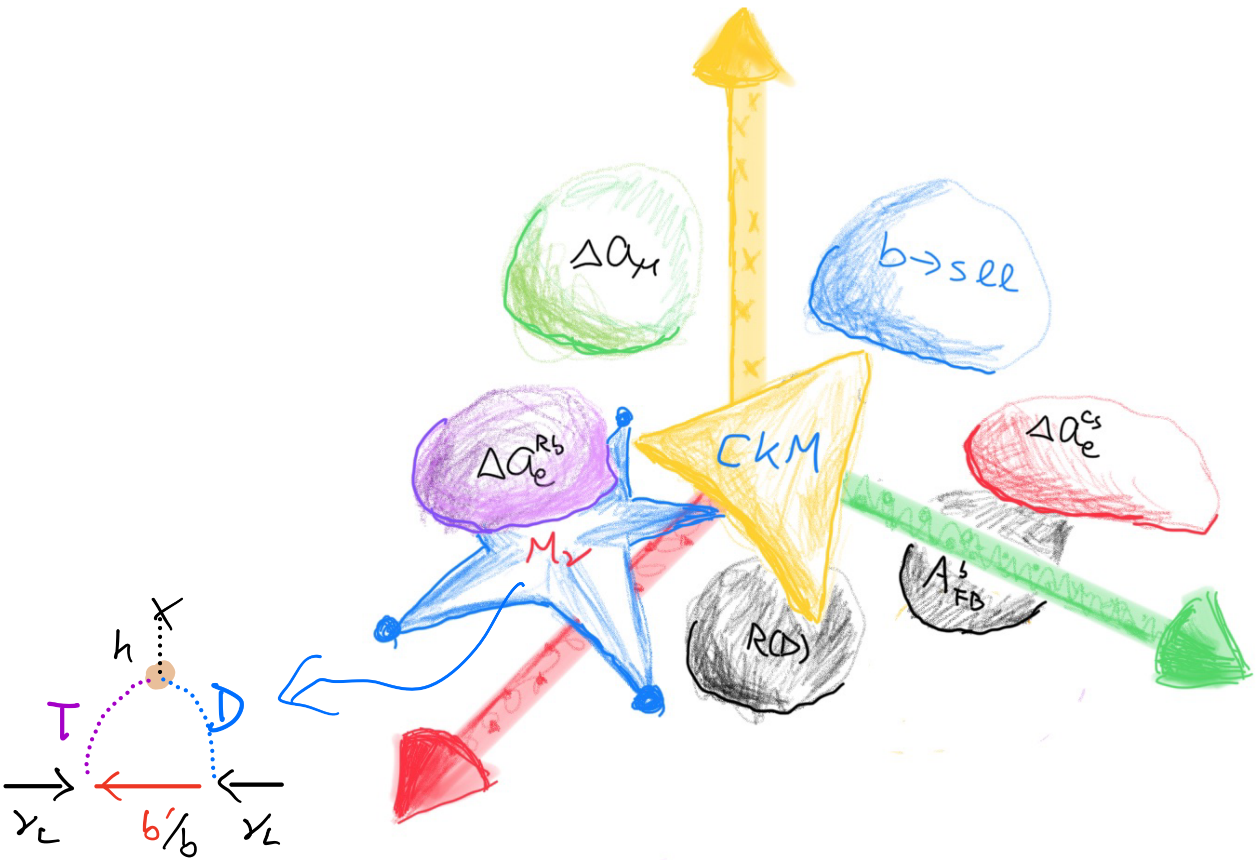
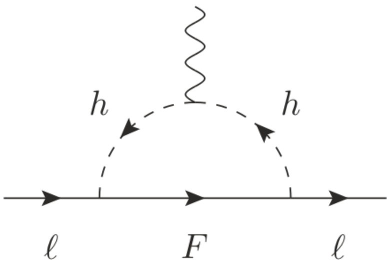
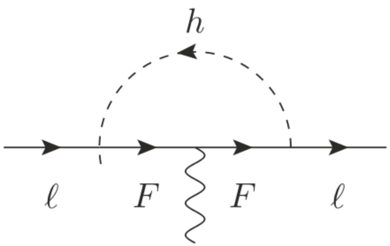


Δa_μ
$b \to s\ell\ell$
CKM
Δa_e^{Rb}
Δa_e^{Cs}
M_ν
A_{FB}^b
R(D)
h
T
D
ν_L
b'/b
ν_L

A general coupling

$$\mathcal{L} \supset \bar{F}(y^l_R \hat{R} + y^l_L \hat{L})\ell h + H.c.$$





charge of F

$$\triangle a^h_l = \frac{-N^F_c(1+Q_F)m^2_l}{8\pi^2}\int_0^1 dx\, x(1-x)\frac{x\frac{|y^l_L|^2+|y^l_R|^2}{2}+\frac{m_F}{m_l}\Re[(y^l_R)^* y^l_L]}{x^2m^2_l + x(m^2_h - m^2_l) + (1-x)m^2_F},$$

$(\Delta a_e^{CS}\, \Delta a_\mu < 0)$

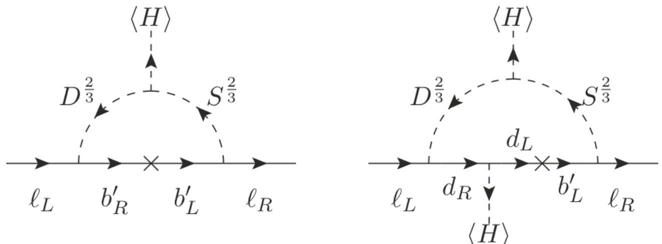
$$\triangle a^F_l = \frac{-N^F_c Q_F m^2_l}{8\pi^2}\int_0^1 dx\, x^2\frac{(1-x)\frac{|y^l_L|^2+|y^l_R|^2}{2}+\frac{m_F}{m_l}\Re[(y^l_R)^* y^l_L]}{x^2m^2_l + x(m^2_F - m^2_l) + (1-x)m^2_h},$$

- If $m_e \ll m_F$,

$$\triangle a_l = \triangle a^F_l + \triangle a^h_l \simeq -\frac{N^F_c \Re[(y^l_R)^* y_L]}{8\pi^2}\left(\frac{m_l}{m_F}\right)\mathcal{J}_{Q_F}\left(\frac{m^2_h}{m^2_F}\right)$$

and

$$\mathcal{J}_Q(\alpha) = \int_0^1 dx\, \frac{x(1-x)+x\,Q}{x+(1-x)\alpha} = \frac{2Q(1-\alpha)(1-\alpha+\alpha\ln\alpha)+(1-\alpha^2+2\alpha\ln\alpha)}{2(1-\alpha)^3}$$

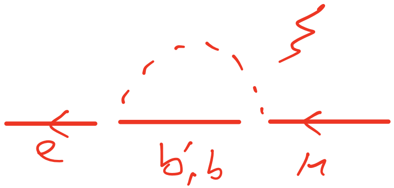


(a) (b)

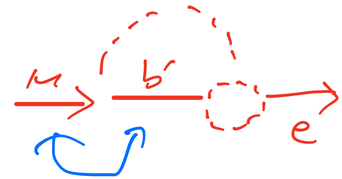
 Δa_e

- NOTE: The diagrams also induce the FCNC $\mu \to e\gamma$ transitions.

e.g.



- A simple arrangement to avoid that,



$\begin{pmatrix} e \\ \mu \end{pmatrix}$ only couples to $\begin{pmatrix} b \\ b' \end{pmatrix}$ or $\begin{pmatrix} b' \\ b \end{pmatrix}$

$\Rightarrow$ b' Plays many roles in the model.

(CKM, Δa_e, Δa_μ, ~~FCNC~~)
$\Uparrow$

Sol-1 :

$$\triangle a_e \simeq 2.28\times 10^{-5}\times[\lambda^D_{eb}\lambda^S_{eb}]\times\left(\frac{\mu_1}{\text{GeV}}\right)\times\mathcal{K}(b_D,b_S)\,,$$

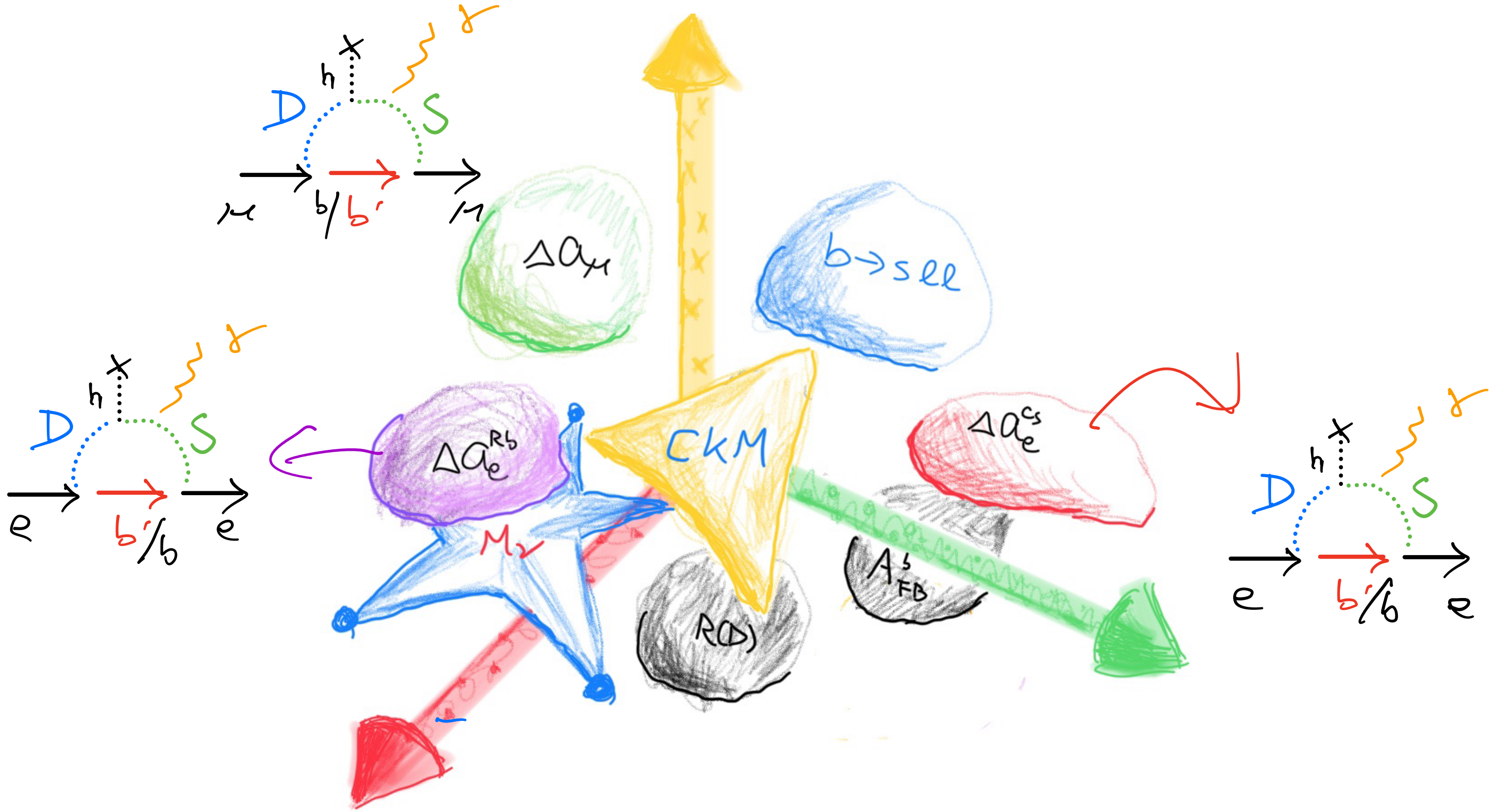
$$\triangle a_\mu \simeq 1.03\times 10^{-10}\times[\lambda^D_{\mu b'}\lambda^S_{\mu b'}]\times\left(\frac{\mu_1}{\text{GeV}}\right)\left(\frac{1.5\text{TeV}}{M_{b'}}\right)^3\times\mathcal{K}(\beta_D,\beta_S)$$

Sol-2 :

$$\Rightarrow\quad \triangle a_e \simeq 5.00\times 10^{-13}\times[\lambda^D_{eb'}\lambda^S_{eb'}]\times\left(\frac{\mu_1}{\text{GeV}}\right)\left(\frac{1.5\text{TeV}}{M_{b'}}\right)^3\times\mathcal{K}(\beta_D,\beta_S)\,,$$

$$\triangle a_\mu \simeq 4.71\times 10^{-3}\times[\lambda^D_{\mu b}\lambda^S_{\mu b}]\times\left(\frac{\mu_1}{\text{GeV}}\right)\times\mathcal{K}(b_D,b_S)\,.$$

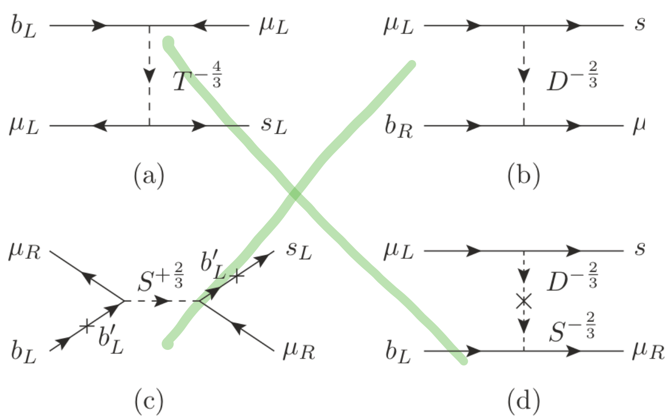
$$\mathcal{K}(a,b)\equiv\frac{\mathcal{J}_{-\frac{1}{3}}(a)-\mathcal{J}_{-\frac{1}{3}}(b)}{b-a}\,.$$

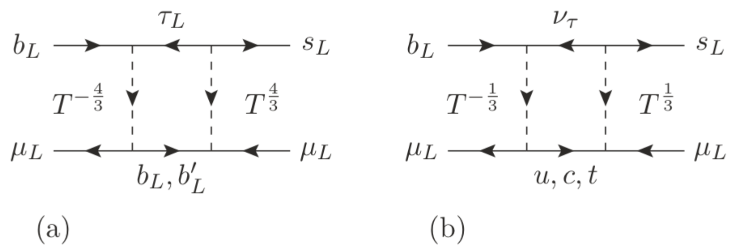


D
h
S
γ
μ
b/b'
μ
Δa_μ
b→see
CKM
Δa_e^Rb
M_ν
Δa_e^Cs
A_FB^b
R(D)
e
b'/b
e

2/6. The Model and its solutions

$b \to s \ell \ell$





$$\mathcal{H}_{\rm eff}^{b\to s\mu\mu} = -\frac{G_F}{\sqrt{2}} \widetilde{V}_{tb}\widetilde{V}_{ts}^* \frac{\alpha}{\pi} \sum_i \mathcal{C}_i \mathcal{O}_i + H.c.$$

$$\mathcal{O}_9 = \left(\bar{s}\gamma^\alpha \hat{L} b\right)\left(\bar{\mu}\gamma_\alpha \mu\right), \quad \mathcal{O}_{10} = \left(\bar{s}\gamma^\alpha \hat{L} b\right)\left(\bar{\mu}\gamma_\alpha \gamma^5 \mu\right),$$

$$\mathcal{O}'_9 = \left(\bar{s}\gamma^\alpha \hat{R} b\right)\left(\bar{\mu}\gamma_\alpha \mu\right), \quad \mathcal{O}'_{10} = \left(\bar{s}\gamma^\alpha \hat{R} b\right)\left(\bar{\mu}\gamma_\alpha \gamma^5 \mu\right).$$

$$\mathcal{H}_{eff(a)}^{b\to s\mu\mu} \simeq -\frac{\lambda^T_{\tau b}(\lambda^T_{\tau s})^*}{64\pi^2}\left(\frac{|\lambda^T_{\mu b'}|^2}{M^2}\mathcal{G}(\beta'_T) + \frac{|\lambda^T_{\mu b}|^2}{m^2}\mathcal{G}(\beta_T)\right)\left(\bar{s}\gamma^\alpha \hat{L} b\right)\left(\bar{\mu}\gamma_\alpha \hat{L}\mu\right) + H.c.,$$

$$\mathcal{H}_{eff(b)}^{b\to s\mu\mu} \simeq \frac{\lambda^T_{\tau b}(\lambda^T_{\tau s})^*}{64\pi^2}\frac{1}{4M_T^2}\left[|\lambda^T_{\mu b'}|^2(s_1^2+s_2^2+s_3^2) + |\lambda^T_{\mu b}|^2\right]\left(\bar{s}\gamma^\alpha \hat{L} b\right)\left(\bar{\mu}\gamma_\alpha \hat{L}\mu\right) + H.c.$$

The box diagram function: $\mathcal{G}(x) = \left[\frac{1}{1-x} + \frac{\ln x}{(1-x)^2}\right]$

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2/6. The Model and its solutions

$b \to s \ell \ell$

$$\mathcal{C}_9 = -\mathcal{C}_{10} \simeq \frac{\sqrt{2}}{128\pi\alpha}\frac{\lambda^T_{\tau b}(\lambda^T_{\tau s})^*}{V_{tb}V^*_{ts}G_F M_T^2}\left[|\lambda^T_{\mu b'}|^2\beta'_T\mathcal{G}(\beta'_T) - \frac{5}{4}|\lambda^T_{\mu b}|^2\right]$$

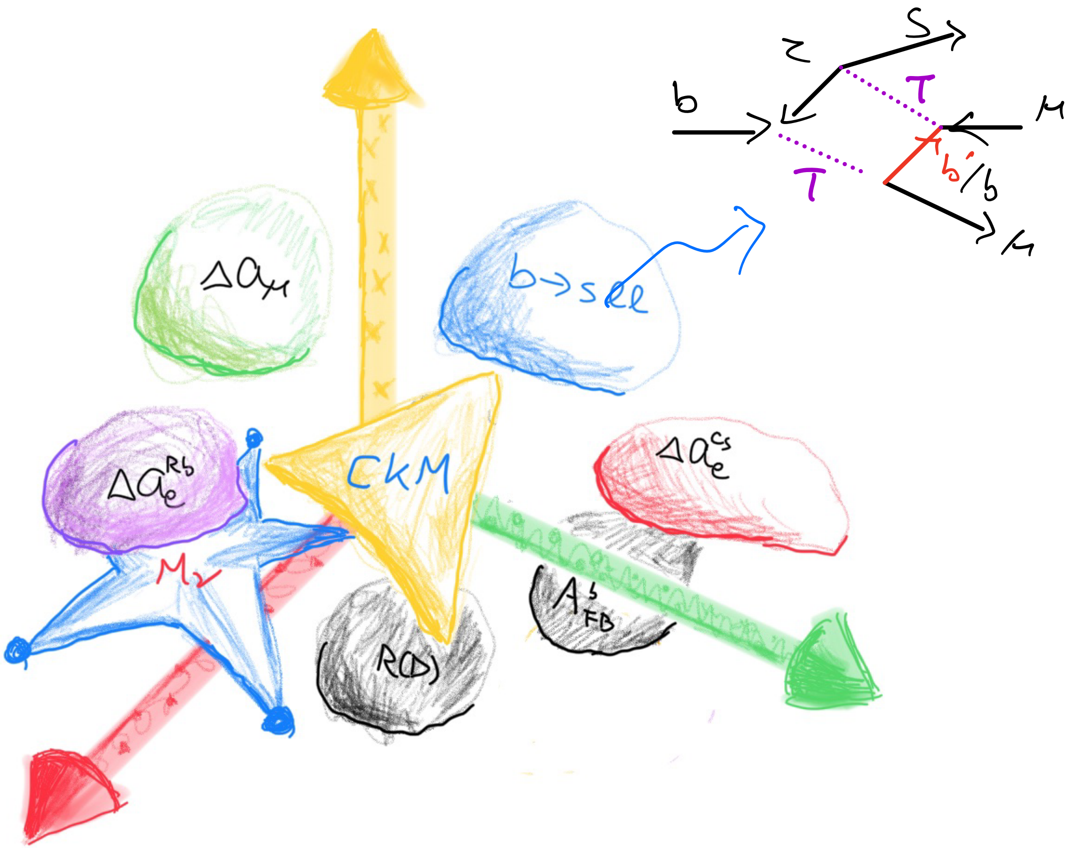
$$\mathcal{C}'_9 = -\mathcal{C}'_{10} = 0\,.$$

(a) (a)+(b)

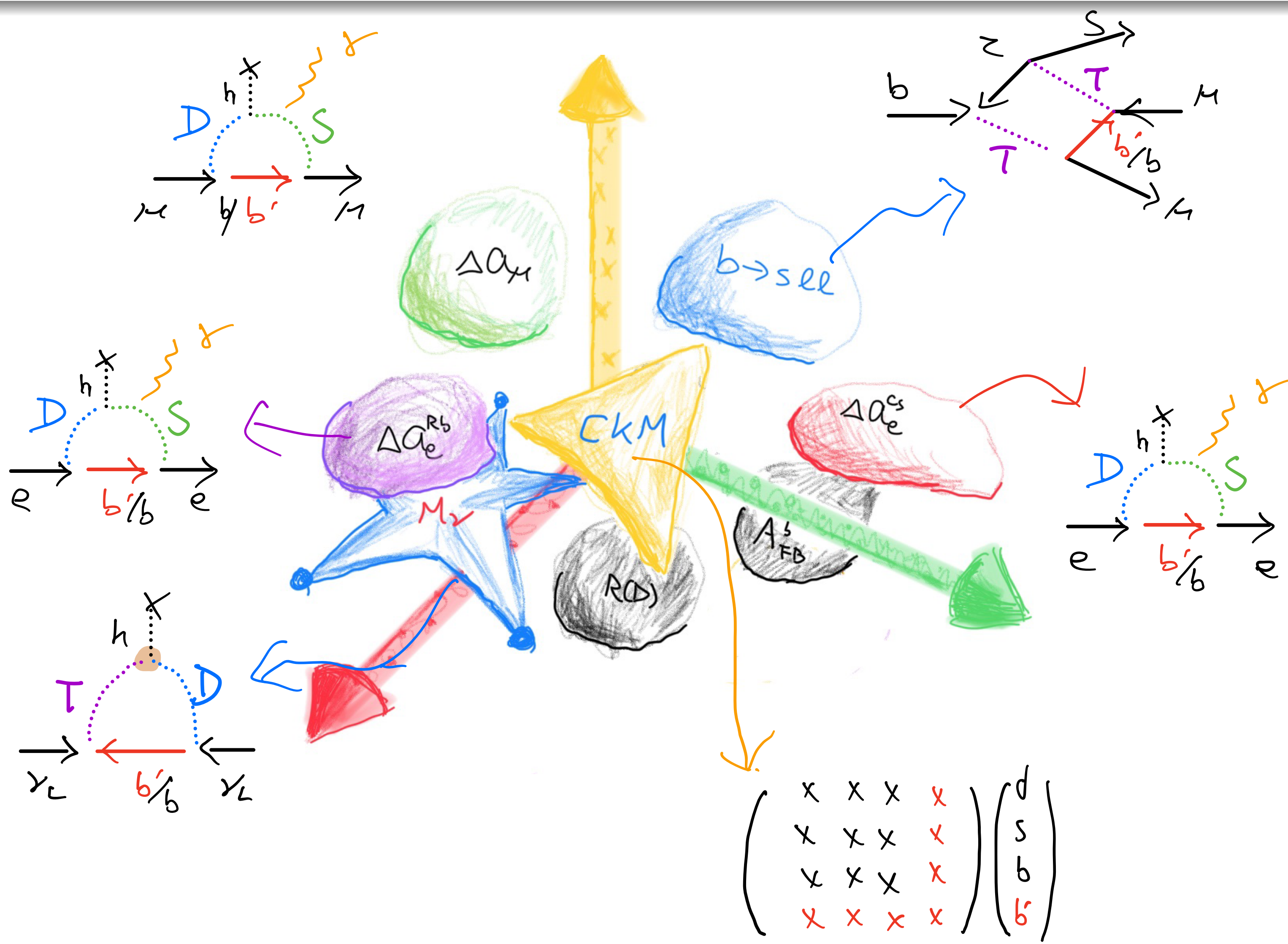
And we adopt the best fit values from Altmannshofer& Stangl 2103.13370

$$(\mathcal{C}_9)^\mu = -(\mathcal{C}_{10})^\mu \simeq -0.41 \pm 0.07\,,$$

$$(\mathcal{C}_9)^e \simeq (\mathcal{C}_{10})^e \simeq (\mathcal{C}'_9)^e \simeq (\mathcal{C}'_{10})^e \simeq 0$$



Δa_μ
$b \to s\ell\ell$
CKM
Δa_e^{Rb}
Δa_e^{Cs}
M_ν
R(D)
A_{FB}^b
b
z
s
T
T
μ
μ
b'/b


γ
h
D
S
μ
b/b′
μ
b
z
S
T
μ
T
b′/b
μ
Δa_μ
b→see
Δa_e^Rb
CKM
Δa_e^Cs
M_ν
A_FB^b
R(D)
e
b′/b
e
T
D
ν_L
b′/b
ν_L
d
s
b
b′

To accommodate the anomalies,

Anomaly	Requirement
m_ν	$\mu_3 m_{b(')} \lambda^D \lambda^T \simeq \mathcal{O}(10^{-5})(\mathrm{GeV})^2$
$\triangle a_e^{Cs[Rb]}, \triangle a_\mu$ (Sol-1)	$\left\{\mu_1 \lambda^D_{eb} \lambda^S_{eb}\,,\ \mu_1 \lambda^D_{\mu b'} \lambda^S_{\mu b'}\right\} \simeq \{(49 \pm 20)[-27 \pm 17], (280 \pm 66)\}\mathrm{GeV}$
$\triangle a_e^{Cs[Rb]}, \triangle a_\mu$ (Sol-2)	$\left\{\mu_1 \lambda^D_{eb'} \lambda^S_{eb'}\,,\ \mu_1 \lambda^D_{\mu b} \lambda^S_{\mu b}\right\} \simeq \{-(20.1 \pm 8.3)[+11.1 \pm 6.9], -(689 \pm 162)\}\mathrm{GeV}$
$b \to s l^+ l^-$	$\lambda^T_{\tau b}(\lambda^T_{\tau s})^*(\lvert\lambda^T_{\mu b'}\rvert^2 + 3.39\lvert\lambda^T_{\mu b}\rvert^2) \simeq -(1.07 \pm 0.18)$
Cabibbo angle anomaly	$\lvert s_1 + 0.233 s_2\rvert \simeq 0.039(7)$

- The minimal set of λ^T to address $b \to s\ell\ell$ & M_ν

$$\mathrm{MinS}_T = \{\lambda^T_{\tau b}\,,\ \lambda^T_{\tau s}\,,\ \lambda^T_{\tau b'}\,,\ \lambda^T_{\mu b'}\,,\ \lambda^T_{\mu b}\}$$

- Need to check the exp. constraints

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- $q q \ell \ell$ operators
- SM Z^0 couplings
- $B_s - \bar{B}_s$ mixing
- $B \to K^{(*)} \nu \bar{\nu}$
- $\tau \to \mu \gamma$, $e \gamma$
- $b \to s \gamma$
- Neutrino data
- $0\nu\beta\beta$ decay

3/6. Constraints

Overview

- $qq\ell\ell$ operators
- SM Z^0 couplings
- $B_s - \bar{B}_s$ mixing
- $B \to K^{(*)} \nu \bar{\nu}$
- $\tau \to \mu\gamma,\ e\gamma$
- $b \to s\gamma$
- Neutrino data
- $0\nu\beta\beta$ decay

$\lambda^T_{ed} \to$ $B^+ \to \pi^+ e\mu$, $B^0 \to \bar{e}\tau$,
$\tau \to e k$, μ-e conv.

$\lambda^T_{es} \to$ $B^+ \to K^+ e\mu$, μ-e conv.

$\lambda^T_{eb} \to$ μ-e conv. $b \to s ee$

$\lambda^T_{\ell_i d} \to$ $K^+ \to \pi^+ \nu\bar{\nu}$

$\lambda^T_{\tau s}$ $\lambda^T_{\tau d} \to$ K-$\bar{K}$ mixing

$\lambda^T_{ed_i} \to$ $\ell \to \ell'\gamma$

$\lambda^T_{\tau d} \to$ $K_L \to \mu\bar{\mu}$

$\lambda^T_{\mu s} \to$ Kaon phys.

● : Tree

● : Loop

$$\mathrm{MinS}_T = \{\lambda^T_{\tau b},\ \lambda^T_{\tau s},\ \lambda^T_{\tau b'},\ \lambda^T_{\mu b'},\ \lambda^T_{\mu b}\}$$

Low energy [qqll] effective operators

$\frac{(\bar q_k\gamma^\mu \hat L q_l)(\bar e_i\gamma_\mu \hat L e_j)}{4M_T^2}$	Wilson Coef.	Constraint	Model
$bb\mu\mu$	$2\lvert\lambda^T_{\mu b}\rvert^2$	211.1 [116]	1.06
$sb\tau\tau$	$2\lambda^T_{\tau b}(\lambda^T_{\tau s})^*$	-	-0.14
$sb\mu\mu$	0[a]	-	0
$sb\mu\tau$	0	-	0
$sb\tau\mu$	$2\lambda^T_{\mu b}(\lambda^T_{\tau s})^*$	0.199[b] [116]	0.11
$uu\tau\mu$	$\left(\tilde V_{ub}(\lambda^T_{\tau b})^* + \tilde V_{ub'}(\lambda^T_{\tau b'})^* + \tilde V_{us}(\lambda^T_{\tau s})^*\right) \times \left(\tilde V^*_{ub}\lambda^T_{\mu b} + \tilde V^*_{ub'}\lambda^T_{\mu b'}\right]$	0.13 [116]	0.0043
$uu\mu\mu$	$\left\lvert\tilde V_{ub}(\lambda^T_{\mu b})^* + \tilde V_{ub'}(\lambda^T_{\mu b'})^*\right\rvert^2$	1.03 [116]	0.017
$uc\mu\mu$	$\left(\tilde V_{ub}(\lambda^T_{\mu b})^* + \tilde V_{ub'}(\lambda^T_{\mu b'})^*\right) \times \left(\tilde V^*_{cb}\lambda^T_{\mu b} + \tilde V^*_{cb'}\lambda^T_{\mu b'}\right)$	0.11[c] [116]	0*
$cc\mu\mu$	$\left\lvert\tilde V_{cb}(\lambda^T_{\mu b})^* + \tilde V_{cb'}(\lambda^T_{\mu b'})^*\right\rvert^2$	52.8 [116]	0*
$cc\tau\mu$	$\left(\tilde V_{cb}(\lambda^T_{\tau b})^* + \tilde V_{cb'}(\lambda^T_{\tau b'})^* + \tilde V_{cs}(\lambda^T_{\tau s})^*\right) \times \left(\tilde V^*_{cb}\lambda^T_{\mu b} + \tilde V^*_{cb'}\lambda^T_{\mu b'}\right)$	211.1 [116]	0*
$tc\mu\mu$	$\left(\tilde V_{tb}(\lambda^T_{\mu b})^* + \tilde V_{tb'}(\lambda^T_{\mu b'})^*\right) \times \left(\tilde V^*_{cb}\lambda^T_{\mu b} + \tilde V^*_{cb'}\lambda^T_{\mu b'}\right)$	-	0*
$tc\tau\tau$	$\left(\tilde V_{tb}(\lambda^T_{\tau b})^* + \tilde V_{tb'}(\lambda^T_{\tau b'})^* + \tilde V_{ts}(\lambda^T_{\tau s})^*\right) \times \left(\tilde V^*_{cb}\lambda^T_{\tau b} + \tilde V^*_{cb'}\lambda^T_{\tau b'} + \tilde V^*_{cs}\lambda^T_{\tau s}\right)$	-	-0.030
$tc\tau\mu$	$\left(\tilde V_{tb}(\lambda^T_{\tau b})^* + \tilde V_{tb'}(\lambda^T_{\tau b'})^* + \tilde V_{ts}(\lambda^T_{\tau s})^*\right) \times \left(\tilde V^*_{cb}\lambda^T_{\mu b} + \tilde V^*_{cb'}\lambda^T_{\mu b'}\right)$	11.35[d]	0*
$tc\mu\tau$	$\left(\tilde V_{tb}(\lambda^T_{\mu b})^* + \tilde V_{tb'}(\lambda^T_{\mu b'})^*\right) \times \left(\tilde V^*_{cb}\lambda^T_{\tau b} + \tilde V^*_{cb'}\lambda^T_{\tau b'} + \tilde V^*_{cs}\lambda^T_{\tau s}\right)$	11.35	0.02
$tu\mu\mu$	$\left(\tilde V_{tb}(\lambda^T_{\mu b})^* + \tilde V_{tb'}(\lambda^T_{\mu b'})^*\right) \times \left(\tilde V^*_{ub}\lambda^T_{\mu b} + \tilde V^*_{ub'}\lambda^T_{\mu b'}\right)$	-	0.09
$tu\tau\tau$	$\left(\tilde V_{tb}(\lambda^T_{\tau b})^* + \tilde V_{tb'}(\lambda^T_{\tau b'})^* + \tilde V_{ts}(\lambda^T_{\tau s})^*\right) \times \left(\tilde V^*_{ub}\lambda^T_{\tau b} + \tilde V^*_{ub'}\lambda^T_{\tau b'} + \tilde V^*_{us}\lambda^T_{\tau s}\right)$	-	-0.03
$tu\tau\mu$	$\left(\tilde V_{tb}(\lambda^T_{\tau b})^* + \tilde V_{tb'}(\lambda^T_{\tau b'})^* + \tilde V_{ts}(\lambda^T_{\tau s})^*\right) \times \left(\tilde V^*_{ub}\lambda^T_{\mu b} + \tilde V^*_{ub'}\lambda^T_{\mu b'}\right)$	11.35	-0.12
$tu\mu\tau$	$\left(\tilde V_{tb}(\lambda^T_{\mu b})^* + \tilde V_{tb'}(\lambda^T_{\mu b'})^*\right) \times \left(\tilde V^*_{ub}\lambda^T_{\tau b} + \tilde V^*_{ub'}\lambda^T_{\tau b'} + \tilde V^*_{us}\lambda^T_{\tau s}\right)$	11.35	0.02

[a] There is no such effective operator at tree-level.
[b] We update this value by using the new data $\mathcal{B}(B^+ \to K^+\mu^+\tau^-) < 4.5\times 10^{-5}$ [1].
[c] We update this value by using the new data $\mathcal{B}(D^+ \to \pi^+\mu^+\mu^-) < 7.3\times 10^{-8}$ [1].
[d] We obtain the limit by using the top quark decay width, $\Gamma_t = 1.42$GeV, and $\mathcal{B}(t\to qll') < 1.86\times 10^{-5}$ [117].

$\frac{(\bar d_k\gamma^\mu \hat L u_l)(\bar\nu_i\gamma_\mu \hat L e_j)}{4M_T^2}$	Wilson Coef.	Constraint	Model
$su\nu_\mu\mu$	0		0
$su\nu_\tau\mu$	$(\lambda^T_{\tau s})^*\left(\tilde V^*_{ub}\lambda^T_{\mu b} + \tilde V^*_{ub'}\lambda^T_{\mu b'}\right)$	3.96	0.010
$su\nu_\tau\tau$	$(\lambda^T_{\tau s})^*\left(\tilde V^*_{ub}\lambda^T_{\tau b} + \tilde V^*_{ub'}\lambda^T_{\tau b'} + \tilde V^*_{us}\lambda^T_{\tau s}\right)$	0.79	0.003
$su\nu_\mu\tau$	0		0
$sc\nu_\mu\mu$	0		0
$sc\nu_\tau\mu$	$(\lambda^T_{\tau s})^*\left(\tilde V^*_{cb}\lambda^T_{\mu b} + \tilde V^*_{cb'}\lambda^T_{\mu b'}\right)$	31.7	0*
$sc\nu_\tau\tau$	$(\lambda^T_{\tau s})^*\left(\tilde V^*_{cb}\lambda^T_{\tau b} + \tilde V^*_{cb'}\lambda^T_{\tau b'} + \tilde V^*_{cs}\lambda^T_{\tau s}\right)$	15.8	0.002
$sc\nu_\mu\tau$	0		0
$bu\nu_\mu\mu$	$(\lambda^T_{\mu b})^*\left(\tilde V^*_{ub}\lambda^T_{\mu b} + \tilde V^*_{ub'}\lambda^T_{\mu b'}\right)$	0.51	0.09
$bu\nu_\tau\mu$	$(\lambda^T_{\tau b})^*\left(\tilde V^*_{ub}\lambda^T_{\mu b} + \tilde V^*_{ub'}\lambda^T_{\mu b'}\right)$	0.51	-0.12
$bu\nu_\tau\tau$	$(\lambda^T_{\tau b})^*\left(\tilde V^*_{ub}\lambda^T_{\tau b} + \tilde V^*_{ub'}\lambda^T_{\tau b'} + \tilde V^*_{us}\lambda^T_{\tau s}\right)$	0.51	-0.03
$bu\nu_\mu\tau$	$(\lambda^T_{\mu b})^*\left(\tilde V^*_{ub}\lambda^T_{\tau b} + \tilde V^*_{ub'}\lambda^T_{\tau b'} + \tilde V^*_{us}\lambda^T_{\tau s}\right)$	0.51	0.02
$bc\nu_\mu\mu$	$(\lambda^T_{\mu b})^*\left(\tilde V^*_{cb}\lambda^T_{\mu b} + \tilde V^*_{cb'}\lambda^T_{\mu b'}\right)$	5.41	0*
$bc\nu_\tau\mu$	$(\lambda^T_{\tau b})^*\left(\tilde V^*_{cb}\lambda^T_{\mu b} + \tilde V^*_{cb'}\lambda^T_{\mu b'}\right)$	5.41	0*
$bc\nu_\tau\tau$	$(\lambda^T_{\tau b})^*\left(\tilde V^*_{cb}\lambda^T_{\tau b} + \tilde V^*_{cb'}\lambda^T_{\tau b'} + \tilde V^*_{cs}\lambda^T_{\tau s}\right)$	5.41	-0.03[a]
$bc\nu_\mu\tau$	$(\lambda^T_{\mu b})^*\left(\tilde V^*_{cb}\lambda^T_{\tau b} + \tilde V^*_{cb'}\lambda^T_{\tau b'} + \tilde V^*_{cs}\lambda^T_{\tau s}\right)$	5.41	0.02

[a] This is the effective operator to address the $R(D^{(*)})$ anomaly.

Carpentier& Davidson, EPJC70,1071

$b \to c\, \ell_i\, \nu \quad (i = e, \mu)$ universality better than $\lesssim 1\%$ [1801.01112]

$[\bar b\, \gamma^\alpha_L c][\bar\nu_\mu \gamma_{\alpha L}\mu]$ $\qquad [\bar b\, \gamma^\alpha_L c][\bar\nu_\tau \gamma_{\alpha L}\mu]$,

intf. SM CC

$\Rightarrow \boxed{\tilde V^*_{cb}\lambda^T_{\mu b} + \tilde V^*_{cb'}\lambda^T_{\mu b'} = 0}$

such that perfect μ-e univ.

NO electron counterpart!!

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 NC int. / A_{FB}

- In the interaction basis ($g^{SM} = T_3 - Q\sin^2\theta_W$),

$$\mathcal{L} \supset \frac{g_2}{c_W}\left[g_L^{SM}\sum_{i=1}^{3}\bar{d}_{Li}\gamma^\alpha d_{Li} + g_R^{SM}\sum_{i=1}^{3}\bar{d}_{Ri}\gamma^\alpha d_{Ri} + g_R^{SM}(\bar{b}'_L\gamma^\alpha b'_L + \bar{b}'_R\gamma^\alpha b'_R)\right] Z_\alpha$$

- In SM $g_R^b = g_L^b + \frac{1}{2}$

$$\mathcal{L} \supset \frac{g_2}{c_W}\left[g_L^{SM}\sum_{i=1}^{4}\bar{d}_{Li}\gamma^\alpha d_{Li} + g_R^{SM}\sum_{i=1}^{4}\bar{d}_{Ri}\gamma^\alpha d_{Ri} + \frac{1}{2}(\bar{b}'_L\gamma^\alpha b'_L)\right] Z_\alpha$$

- Then, in the mass basis, Z d-b

$$\mathcal{L} \supset \frac{g_2}{c_W}\left[\sum_{\alpha=s,d,b,b'}\bar{d}_\alpha\gamma^\alpha(g_L^{SM}\hat{L} + g_R^{SM}\hat{R})d_\alpha\right] Z_\mu + \frac{g_2}{2c_W}\sum_{\alpha,\beta=s,d,b,b'}\kappa_{\alpha\beta}\left[(\bar{d}_\alpha\gamma^\alpha\hat{L}d_\beta)\right] Z_\alpha ,\qquad \kappa_{\alpha\beta} \equiv (U_L^d)_{\alpha 4}[(U_L^d)_{\beta 4}]^*$$

In our parameterization, the FCNC couplings

$$\kappa_{sd} = \kappa_{ds} = s_1 s_2 c_2 c_3^2\,,\ \kappa_{sb} = \kappa_{bs} = s_2 s_3 c_3\,,\ \kappa_{bd} = \kappa_{db} = s_1 s_3 c_2 c_3$$

- To avoid Tree-level FCNC mediated by Z^0, ONLY 1 $\theta \neq 0$

- For that particular θ_F

$$g_{d_F,R}^{SM} \Rightarrow g_{d_i,R}^{SM}\,,\ g_{d_F,L}^{SM} \Rightarrow g_{d_i L}^{SM} + \frac{1}{2}\left|(U_L^d)_{4d_F}\right|^2$$

 NC int. / A_{FB}

$$A_F, A_{FB} \propto \frac{g_L^2 - g_R^2}{g_L^2 + g_R^2}\,,\ \Gamma \propto g_L^2 + g_R^2$$

$g_L^{SM} \sim -0.423$

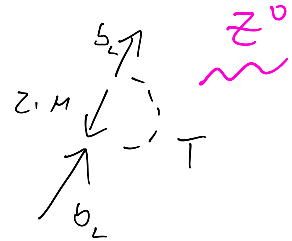
$g_R^{SM} \sim 0.077$

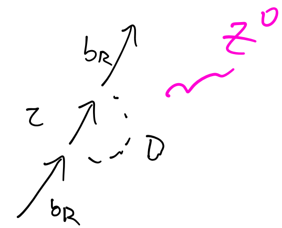
- Long standing LEP puzzle: $A^b_{FB} \sim -2.3\delta$, requires $\theta_3 \neq 0$ $(b\text{-}b')$, $\Longleftrightarrow$ CKM

  Only $\theta_1 \neq 0$ is viable to satisfy all Exp. limits

$$|s_1| \simeq 0.039(7)$$

negligible δA^d_{FB}





- How about loop?

In $\overline{\mathrm{MS}}$ and on-shell renormalization

$$\delta g_L^b \simeq \frac{|\lambda^T_{\tau b}|^2 + |\lambda^T_{\mu b}|^2}{64\pi^2}\left[\left(-1+\frac{5}{3}s_W^2\right)\frac{1}{9\beta_Z} - s_W^2\,\frac{2\ln\beta_Z + \frac{1}{3} + i\pi/2}{3\beta_Z}\right],$$

$$\delta g_R^b \simeq \frac{|\lambda^D_{\tau b}|^2}{64\pi^2}\left[\left(-\frac{1}{3}s_W^2\right)\frac{1}{9\beta_Z} + s_W^2\,\frac{2\ln\beta_Z + \frac{1}{3} + i\pi/2}{3\beta_Z}\right],$$

- $|\delta g^b_{L,R}| \sim O(10^{-5})\,|\lambda^{T,D}|^2$, Not helpful to A^b_{FB}

- Wait for future Z-pole exp. (FCC-ee, ILC, CEPC….)

 Neutrino data

- For M_ν, Δa_e more parameters are needed ($\mathrm{MinS}_T = \{\lambda^T_{\tau b},\ \lambda^T_{\tau s},\ \lambda^T_{\tau b'},\ \lambda^T_{\mu b'},\ \lambda^T_{\mu b}\}$)

$\lambda^D_{eb'}\lambda^T_{eb'}$ $\cancel{\ }$

$$\mathrm{MinS} = \mathrm{MinS}_T \cup \Big\{\lambda^D_{eb'}, \underbrace{\lambda^D_{\tau b'}, \lambda^D_{\mu b}, \lambda^D_{\tau b}}_{\text{for } m_\nu}, \underbrace{\lambda^S_{eb'}, \lambda^S_{\mu b}}_{\text{for } \Delta a_e, \Delta a_\mu}\Big\} \,.$$

$$\mathcal{M}^\nu \simeq N^\nu \begin{pmatrix} 0 & \lambda^D_{eb'}\lambda^T_{\mu b'} & \lambda^D_{eb'}\lambda^T_{\tau b'} \\ \lambda^D_{eb'}\lambda^T_{\mu b'} & 2\rho_b\lambda^D_{\mu b}\lambda^T_{\mu b} & \rho_b(\lambda^D_{\mu b}\lambda^T_{\tau b} + \lambda^D_{\tau b}\lambda^T_{\mu b}) + \lambda^D_{\mu b'}\lambda^T_{\tau b'} \\ \lambda^D_{eb'}\lambda^T_{\tau b'} & \rho_b(\lambda^D_{\mu b}\lambda^T_{\tau b} + \lambda^D_{\tau b}\lambda^T_{\mu b}) + \lambda^D_{\mu b'}\lambda^T_{\tau b'} & 2\rho_b\lambda^D_{\tau b}\lambda^T_{\tau b} + 2\lambda^D_{\tau b'}\lambda^T_{\tau b'} \end{pmatrix}$$

- $M_\nu^{ee} = 0$, only NH is allowed

$$\rho_b = m_b/M_{b'} \text{ and } N^\nu = \frac{3\mu_3 v_0 M_{b'}}{32\pi^2 M^2_{LQ}}$$

- $$\mathcal{M}^\nu \simeq \begin{pmatrix} 0 & 0.90792 & 0.13812 \\ 0.90792 & -2.4923 & -2.7643 \\ 0.13812 & -2.7643 & -1.9353 \end{pmatrix} \times 10^{-2}\mathrm{eV}$$

$$\theta_{12} \simeq 33.0^\circ\,, \quad \theta_{23} \simeq 48.7^\circ\,, \quad \theta_{13} \simeq 8.6^\circ\,, \quad \delta_{CP} = 0^\circ\,,$$
$$\triangle m^2_{21} \sim 7.47\times 10^{-5}\mathrm{eV}^2\,, \quad \triangle m^2_{31} \sim 2.53\times 10^{-3}\mathrm{eV}^2\,.$$

(Just one out of ∞ example)

v.s. 1σ best fit (w. SK atm) NuFit

$$\theta_{12} \in (32.7-34.21)^\circ, \quad \theta_{23} \in (48.0-50.1)^\circ, \quad \theta_{13} \in (8.45-8.69)^\circ, \quad \delta_{CP} \in (173-224)^\circ,$$
$$\triangle m^2_{21} \in (7.22-7.63)\times 10^{-5}\mathrm{eV}^2, \quad \triangle m^2_{31} \in (2.489-2.543)\times 10^{-3}\mathrm{eV}^2.$$

Numerical Results:

The neutrino mass pattern $(\sim 1\sigma)$

Δa_e^{cs} $[\Delta a_e^{Rb}]$, Δa_μ, the Cabibbo angle, b⟶ sll anomalies

can be accommodated by the following viable model parameters:

$$M_{LQ} \simeq 1.0\,\mathrm{TeV}\,, \quad M_{b'} = 1.5\,\mathrm{TeV}\,, \quad \mu_1 = 2.3[-0.82]\,\mathrm{TeV}\,, \quad \mu_3 \simeq 0.5\,\mathrm{keV}\,,$$
$$\mu_1 \lambda^S_{eb'} \lambda^D_{eb'} = -12[4]\mathrm{GeV}\,, \quad \mu_1 \lambda^S_{\mu b} \lambda^D_{\mu b} = -690\mathrm{GeV}\,,$$
$$\theta_2 = \theta_3 = 0\,, \quad \sin\theta_1 = 0.039\,,$$
$$\lambda^T_{\mu b'} \simeq -3.3\,, \quad \lambda^T_{\tau b'} \simeq -0.51\,, \quad \lambda^T_{\mu b} \simeq -0.72\,, \quad \lambda^T_{\tau b} \simeq 0.93\,, \quad \lambda^T_{\tau s} \simeq -0.08\,,$$
$$\lambda^D_{eb'} \simeq -0.002\,, \quad \lambda^D_{\mu b} \simeq 3.4\,, \quad \lambda^D_{\tau b'} \simeq 0.008\,, \quad \lambda^D_{\tau b} \simeq -0.58\,,$$

Note that $\mathcal{O}\left(\frac{\mu_3}{M_{LQ}}\right) \sim 10^{-9}$ ⤳ global L#.

4/6. Phenomenological consequences

- $B^+ \to K^+ \mu^+ \tau^-$, $B_s - \bar{B}_s$ mixing, $D^+ \to \pi^+ \mu^+ \mu^-$, $\tau \to \mu \gamma$

  stringently set the parameter space boundaries.

- $b \to s \tau \tau$ at tree-level

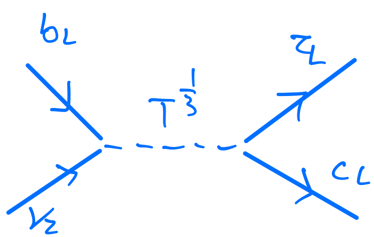
$$\mathcal{H}_{\text{eff}}^{b \to s\tau\tau} \simeq -\frac{G_F}{\sqrt{2}} \widetilde{V}_{tb} \widetilde{V}_{ts}^* \frac{\alpha}{\pi} \mathcal{C}^{bs\tau\tau} \left[\bar{s}\gamma^\alpha \hat{L} b\right] \left[\bar{\tau}\gamma_\alpha (1-\gamma^5)\tau\right] + H.c.\,,$$

$$\mathcal{C}^{bs\tau\tau} \simeq \frac{\sqrt{2}\pi}{4\alpha} \frac{\lambda_{\tau b}^T (\lambda_{\tau s}^T)^*}{\widetilde{V}_{tb}\widetilde{V}_{ts}^* G_F M_T^2} = 23.2 \times \left(\frac{\text{TeV}}{M_T}\right)^2, \quad \left(\text{c.f. } C_{SM}^{bs\tau\tau} \sim -4.3 \right)$$

$\Rightarrow$ $Br(B_s \to \tau^+\tau^-) \simeq 10^{-5}$ still $\ll \sim O(10^{-3})$

$B_s \to \tau^+\tau^-$ LHCb [1703.02508]
$B^+ \to K^+\tau^+\tau^-$ BaBar [1605.09637]

- $R(D^{(*)})$



$R(D^{(*)})$ needs $C_{V_L} \simeq 0.08$ [1904.09311]
but $C_{V_L}^{NP} \lesssim 0.01$ in this model
(with real parameters)

$$\mathcal{H}_{\text{eff}}^{CC} \supset -\left[\frac{\lambda_{\tau s}^T (\lambda_{\tau b}^T)^* \widetilde{V}_{cs} + \lambda_{\tau b}^T (\lambda_{\tau b'}^T)^* \widetilde{V}_{cb'} + |\lambda_{\tau b}^T|^2 \widetilde{V}_{cb}}{4M_T^2}\right] \left(\bar{c}\gamma^\alpha \hat{L} b\right) \left(\bar{\tau}\gamma_\alpha \hat{L}\nu_\tau\right) + H.c.$$

4/6. Phenomenological consequences

decay BR's

For the benchmark point,

$$\mathcal{B}(T^{-\frac{1}{3}} \to b\nu_\mu) \simeq 18.9\%\,, \quad \mathcal{B}(T^{-\frac{1}{3}} \to b\nu_\tau) \simeq 30.9\%\,, \quad \mathcal{B}(T^{-\frac{1}{3}} \to s\nu_\tau) \simeq 2.1 \times 10^{-3}\,,$$
$$\mathcal{B}(T^{-\frac{1}{3}} \to \tau t) \simeq 30.8\%\,, \quad \mathcal{B}(T^{-\frac{1}{3}} \to \mu t) \simeq 18.9\%\,, \quad \mathcal{B}(T^{-\frac{1}{3}} \to \tau c) \simeq 2.0 \times 10^{-3}\,.$$

$$\mathcal{B}(T^{\frac{2}{3}} \to t\nu_\mu) \simeq 37.9\%\,, \quad \mathcal{B}(T^{\frac{2}{3}} \to t\nu_\tau) \simeq 61.7\%\,, \quad \mathcal{B}(T^{\frac{2}{3}} \to c\nu_\tau) \simeq 0.4\%\,,$$
$$\mathcal{B}(T^{-\frac{4}{3}} \to b\mu^-) \simeq 37.9\%\,, \quad \mathcal{B}(T^{-\frac{4}{3}} \to b\tau^-) \simeq 61.7\%\,, \quad \mathcal{B}(T^{-\frac{4}{3}} \to s\tau^-) \simeq 0.4\%\,.$$

$$\mathcal{B}(D^{-\frac{1}{3}} \to b\bar{\nu}_\mu) \simeq 97.1\%\,, \qquad \mathcal{B}(D^{-\frac{1}{3}} \to b\bar{\nu}_\tau) \simeq 2.9\%\,,$$
$$\mathcal{B}(D^{\frac{2}{3}} \to b\mu^+) \simeq 97.1\%\,, \qquad \mathcal{B}(D^{\frac{2}{3}} \to b\tau^+) \simeq 2.9\%\,,$$
$$\mathcal{B}(S^{\frac{2}{3}} \to b\mu^+) \simeq 100\%\,,$$

$$\mathcal{B}(b' \to uW^-) \simeq 1.2\%\,, \quad \mathcal{B}(b' \to cW^-) \simeq 6 \times 10^{-4}\,, \quad \mathcal{B}(b' \to tW^-) \simeq 9 \times 10^{-7}\,,$$
$$\mathcal{B}(b' \to \bar{\nu}T^{-\frac{1}{3}}) \simeq 19.7\%\,, \quad \mathcal{B}(b' \to \mu^+T^{-\frac{4}{3}}) \simeq 38.5\%\,,$$
$$\mathcal{B}(b' \to \tau^+T^{-\frac{4}{3}}) \simeq 0.9\%\,, \quad \mathcal{B}(b' \to eS^{\frac{2}{3}}) \simeq 39.7\%\,,$$

Very diff. from the simple assumptions implemented
in searching for LQ, b'. (cf. 100% $b' \to Wt, bZ, bH$)

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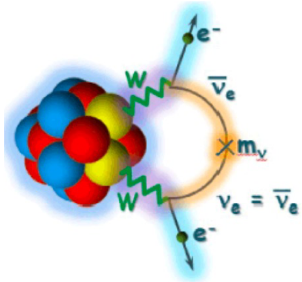
$0\beta\nu\nu$ - decay

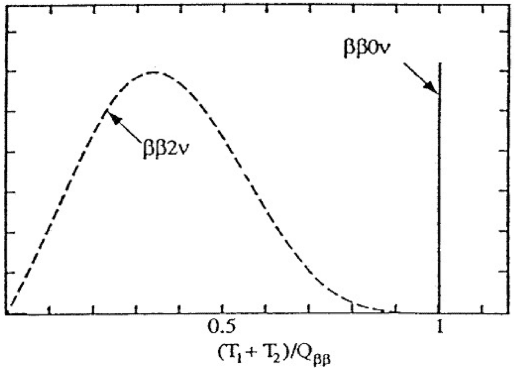
Table 2 $T_{1/2}^{0\nu}$ and $\langle m_{\beta\beta} \rangle$ limits (90% CL) from the most recent measurements, sorted by mass number

Isotope	$T_{1/2}^{0\nu}$ ($\times 10^{25}$ years)	$\langle m_{\beta\beta} \rangle$ (eV)	Experiment	Reference
^{48}Ca	$>5.8 \times 10^{-3}$	<3.5–22	ELEGANT-IV	159
^{76}Ge	>8.0	<0.12–0.26	GERDA	160
	>1.9	<0.24–0.52	MAJORANA DEMONSTRATOR	161
^{82}Se	$>3.6 \times 10^{-2}$	<0.89–2.43	NEMO-3	162
^{96}Zr	$>9.2 \times 10^{-4}$	<7.2–19.5	NEMO-3	163
^{100}Mo	$>1.1 \times 10^{-1}$	<0.33–0.62	NEMO-3	164
^{116}Cd	$>2.2 \times 10^{-2}$	<1.0–1.7	Aurora	165
^{128}Te	$>1.1 \times 10^{-2}$	NE	C. Arnaboldi et al.	166
^{130}Te	>1.5	<0.11–0.52	CUORE	126
^{136}Xe	>10.7	<0.061–0.165	KamLAND-Zen	167
	>1.8	<0.15–0.40	EXO-200	168
^{150}Nd	$>2.0 \times 10^{-3}$	<1.6–5.3	NEMO-3	169

Annu. Rev. Nucl. Part. Sci. 2019.69:219-251.



$\propto |M^{\nu}_{ee}|^2$



$Q_{\beta\beta} \equiv M(A,Z) - M(A,Z+2)$

Due to μ-e conv. even with $\lambda^T_{eb'} \neq 0$

$|M^{\nu}_{ee}| \lesssim 3 \times 10^{-4}$ eV

5/6. Origin of the flavor pattern?

- We need a very special flavor pattern (usually call for some nontrivial flavor symmetry)

- In 4D QFT, the Higgs Yukawa after SSB

$$y \overline{\psi_{1L}} \psi_{2R} H \longrightarrow \frac{y v_0}{\sqrt{2}} \overline{\psi_{1L}} \psi_{2R} \Rightarrow m \propto y$$

- In 5D, with extra-dimension z

$$\psi_{1L}^{5D} = \psi_{1L}^{4D}(x^\mu)\, \phi_1(z) \qquad \psi_{2R}^{5D} = \psi_{2R}^{4D}(x^\mu)\, \phi_2(z)$$

$$H^{5D} = H^{4D}(x^\mu)\, f(z), \qquad \mathcal{L}_{5D} \sim y_{5D}\, \overline{\psi_{1L}^{5D}}\, \psi_{2R}^{5D}\, H^{5D}$$

- Integrating out the 5-th dim.

$$\mathcal{L}_{4D} = \int dz\, \mathcal{L}_{5D} \propto \overline{\psi_{1L}^{4D}}\, \psi_{2R}^{4D}\, H^{4D} \int dz\, \phi_1^*(z)\, \phi_2(z)\, f(z)$$

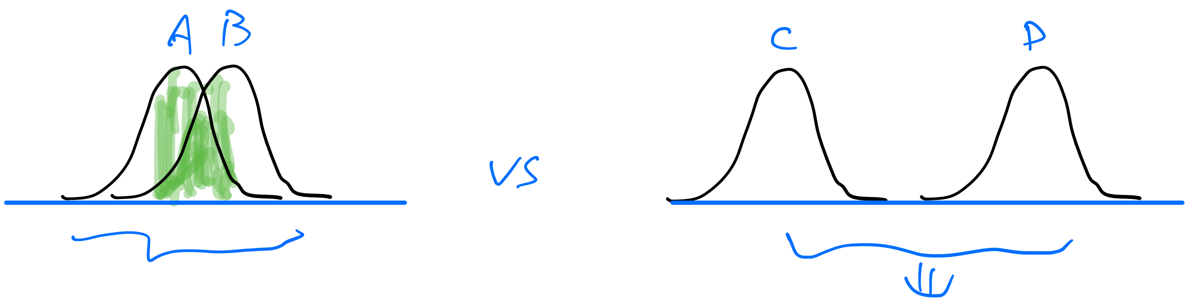
$$\Rightarrow y_{4D} \sim y_{5D} \times \int dz\, \phi_1^*(z)\, \phi_2(z)\, f(z)$$

- One toy model : split fermion (Arkani-Hamed, 9903417)

All $\phi_i(z)$ ~ Gaussian with universal σ_{SF} , cluster

$$y_{4D} \sim \exp\left[-\frac{\Delta z^2}{2\sigma_{SF}^2}\right],$$

Δz	1	2	5
exp	~ 0.6	~ 0.13	10^{-11}



The effective $y_{4D}^{AB} \sim O(1)$ $y_{4D}^{CD} \lll 1$

5/6. Origin of the flavor pattern?

- One example SF configuration

$$\{N_T, N_D, N_S\} = \{4.5, 6.2, 5.5\}.$$

and

$$\{z_{\tau_L}, z_{\mu_L}, z_{e_L}, z_{\mu_R}, z_{e_R}\} = \{0,\ -0.49,\ 7.75[7.80],\ -4.99[-4.72],\ -0.89[-0.97]\}\,,$$

$$\{z_{d_L}, z_{s_L}, z_{b_L}, z_{b'_L}, z_{b_R}, z_{b'_R}\} = \{-5.27[-5.53],\ 2.86[2.90],\ -2.14[-2.13],\ -1.90[-1.95],\ -2.06[-2.09],\ 3.66[3.74]\}\,,$$

which is able to reproduce every parameter within ∼50%

$$|\lambda^T_{\mu b'}| = 1.66[1.56]\,, \quad |\lambda^T_{\tau b'}| = 0.74[0.68]\,, \quad |\lambda^T_{\mu b}| = 1.15[1.17]\,,$$

$$|\lambda^T_{\tau b}| = 0.46[0.46]\,, \quad |\lambda^T_{\tau s}| = 7.5[6.8]\times 10^{-2}\,,$$

$$|\lambda^D_{eb'}| = 1.5[1.6]\times 10^{-3}\,, \quad |\lambda^D_{\mu b}| = 1.78[1.71]\,, \quad |\lambda^D_{\tau b'}| = 7.5[5.8]\times 10^{-3}\,, \quad |\lambda^D_{\tau b}| = 0.74[0.69]\,,$$

$$|\lambda^S_{eb'}| = 3.31[3.42]\,, \quad |\lambda^S_{\mu b}| = 9.4[19.2]\times 10^{-2}\,.$$

-

$$|\lambda^D_{eb}| = 7.5[3.6]\times 10^{-21}\,, \quad |\lambda^D_{\mu b'}| = 1.1[0.8]\times 10^{-3}\,,$$

$$|\lambda^T_{ed}| = 7.0[0.13]\times 10^{-37}\,, \quad |\lambda^T_{es}| = 2.9[2.8]\times 10^{-5}\,, \quad |\lambda^T_{eb}| = 2.6[1.8]\times 10^{-21}\,,$$

$$|\lambda^T_{eb'}| = 2.7[1.1]\times 10^{-20}\,, \quad |\lambda^T_{\mu d}| = 4.8[1.4]\times 10^{-5}\,, \quad |\lambda^T_{\tau d}| = 4.2[1.0]\times 10^{-6}\,,$$

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5/6. Origin of the flavor pattern?

- In addition to the hierarchical Yukawa, the nearly conserved L#, or

$$\mathcal{O}\left(\frac{\mu_3}{M_{LQ}}\right) \sim 10^{-9}$$

can be easily arranged in this 5D model.

- Recall that, $\mu_3 \sim 0.5\,\mathrm{KeV}$, $M_{LQ}, M_b', \mu_1 \sim \mathcal{O}(\mathrm{TeV})$

$$\mathcal{L} \supset \mu_3 \{H, \tilde{D}\} \otimes T + \mu_1 [H, D] S^{-\frac{1}{3}}$$

$\Rightarrow$ D&T have different orbiting parties (such that nearly orthogonal to each other)

D&S have the same …

Overlapping $\sim \mathcal{O}(1)$

e.g. T: (+,-), D, S: (-,+) on the $S_1/Z_2 \times Z_2$ orbifold

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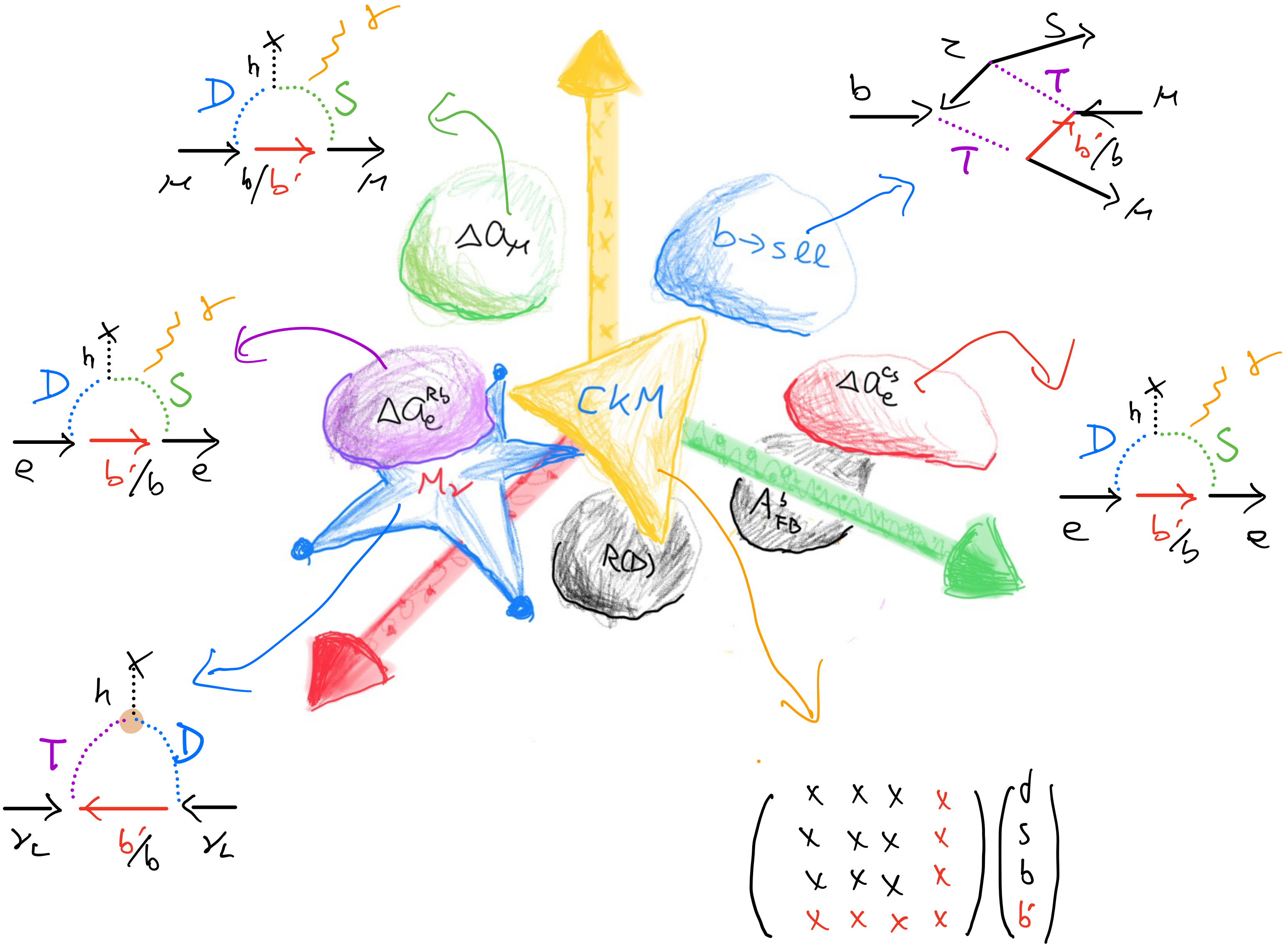
6/6. Conclusion

- Neutrino mass, $b \to sll$, $\triangle a_\mu$, $\triangle a_e^{Cs[Rb]}$, and CKM anomalies can be accommodated in SM$+$ 3 scalar leptoquarks $(3,3,-1/3),(3,2,1/6),(3,1,2/3)$ $+$vector b' with $U(1)_B$.
- Viable benchmark point with minimal set of real parameters.
- Solid prediction: normal hierarchy with $\mathcal{M}^\nu_{ee} \lesssim 3 \times 10^{-4}$ eV.
- Nontrivial leptoquark/b' decay branching ratios.
- Nearly conserved global Lepton number
- Split fermion is one possible origin of the flavor pattern


D
S
h
γ
μ
b/b'
CKM
Δa_μ
b→sℓℓ
Δa_e^{Rb}
Δa_e^{Cs}
M_ν
R(D)
A^b_FB
T
Z
ν_L
e
d
s
b
b'