Addressing the CKM unitarity problem with a vector-like up quark

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Cofinanciado por:

Overview

1. Motivation
2. Lagrangian and Parameterisation
3. New Physics and Results
4. Conclusions

Motivation

The SM has unitary quark and leptonic mixing matrices. The νSM (SM + ν_R) has a non-unitary leptonic mixing matrix, in principle. What if V_{CKM} is also not unitary?

$$\begin{aligned}\Delta_1 &= 1 - |V_{11}|^2 - |V_{12}|^2 - |V_{13}|^2 \\ \Delta_2 &= 1 - |V_{21}|^2 - |V_{22}|^2 - |V_{23}|^2 \\ \Delta_3 &= 1 - |V_{31}|^2 - |V_{32}|^2 - |V_{33}|^2\end{aligned}$$

Let's define this measure for the deviations from unitarity (DU) of mixing matrices $V \equiv V_{CKM}$.

Motivation

Experiments are pointing towards non-zero deviations from unitarity (DU) in the quark sector:

- **CKM Unitarity Problem/Cabibbo Angle Anomaly** : Improved measurements of V_{ud} seem to indicate $\sqrt{\Delta_1} \sim 0.04$
  Solution(?): VLQs (one of many, arguably the simplest)

Motivation: How to deal with DU?

Approximations are common in literature.

- VLQs: Common assumption that heavy VLQs only couple to third generation quarks.

What if you want to study a region... **where these approximations fail?**

What if you want to ... **perform a general scan of the parameter space,** without biases?

An up VLQ as a solution

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In [1], one up VLQ was introduced to explain the CKM unitarity problem.

[1]Branco, G.C., Penedo, J.T., Pereira, P.M.F. et al. J. High Energ. Phys. 2021, 99 (2021). https://doi.org/10.1007/JHEP07(2021)099

VLQs I

$$\begin{aligned}
\Delta \equiv \Delta_1 &= 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = \left|\mathcal{V}^*_{L_{41}}\right|^2 = s_{14}^2 \\
\Delta_2 &= 1 - |V_{cd}|^2 - |V_{cs}|^2 - |V_{cb}|^2 = \left|\mathcal{V}^*_{L_{42}}\right|^2 = c_{14}^2\, s_{24}^2 \\
\Delta_3 &= 1 - |V_{td}|^2 - |V_{ts}|^2 - |V_{tb}|^2 = \left|\mathcal{V}^*_{L_{43}}\right|^2 = c_{14}^2\, c_{24}^2\, s_{34}^2
\end{aligned}$$

The experimental data suggests $\sqrt{\Delta} \sim 0.04$ [2]

[2] B. Belfatto, R. Beradze and Z. Berezhiani, Eur. Phys. J. C 80 (2020) 149 [1906.02714]

Lagrangian

$$\mathcal{L}_{\mathrm{M}} = -\begin{pmatrix}\overline{d}_L^0 & \overline{D}_L^0\end{pmatrix} \mathcal{M}_d \begin{pmatrix} d_R^0 \\ D_R^0 \end{pmatrix} - \begin{pmatrix}\overline{u}_L^0 & \overline{U}_L^0\end{pmatrix} \mathcal{M}_u \begin{pmatrix} u_R^0 \\ U_R^0 \end{pmatrix} + \mathrm{h.c.}$$

$$\mathcal{M}_q = \begin{array}{c} \left(\begin{array}{c:c} m_q & \overline{m}_q \\ \hdashline \overline{M}_q & M_q \end{array}\right) \\ \hphantom{(}\underbrace{\hphantom{M_q}}_{3}\;\underbrace{\hphantom{M_q}}_{n_q} \end{array} \begin{array}{l} \}\, 3 \\ \}\, n_q \\ \vphantom{x} \end{array}$$

Lagrangian II

$$\mathcal{V}_L^{q\dagger}\,\mathcal{M}_q\,\mathcal{V}_R^q = \mathcal{D}_q$$

$$\mathcal{V}_\chi^q = \left(\begin{array}{c} A_\chi^q \\ \hdashline B_\chi^q \end{array}\right) \qquad \chi = L, R \quad , \; q = u, d$$

$A = 3 \times (3+n)$, $B = n \times (3+n)$

Charged Currents:

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \begin{pmatrix} \overline{u}_L & \overline{U}_L \end{pmatrix} V\,\gamma^\mu \begin{pmatrix} d_L \\ D_L \end{pmatrix} W_\mu^+ + \text{h.c.}$$

$$V = A_L^{u\dagger} A_L^d$$

Lagrangian III

Neutral Interactions:

$$\mathcal{L}_H = -\frac{h}{v}\left[\begin{pmatrix} \overline{q}_L & \overline{Q}_L \end{pmatrix} F^q \, \mathcal{D}_q \begin{pmatrix} q_R \\ Q_R \end{pmatrix} \right] + \text{h.c.}$$

$$\mathcal{L}_H = -\frac{h}{v}\left[\begin{pmatrix} \overline{n}_L & \overline{N}_L \end{pmatrix} F \, \mathcal{D} \begin{pmatrix} n_L^c \\ N_L^c \end{pmatrix} \right] + \text{h.c.}$$

$$F^q = A_L^{q\dagger} A_L^q$$

Parameterisation

$$\mathcal{V}_L^\dagger \mathcal{M}_u \mathcal{V}_R = \mathcal{D}_u$$

$$\mathcal{V}_L^\dagger = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_{34} & s_{34} \\ 0 & 0 & -s_{34} & c_{34} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{24} & 0 & s_{24}e^{-i\delta_{24}} \\ 0 & 0 & 1 & 0 \\ 0 & -s_{24}e^{i\delta_{24}} & 0 & c_{24} \end{pmatrix} \begin{pmatrix} c_{14} & 0 & 0 & s_{14}e^{-i\delta_{14}} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_{14}e^{i\delta_{14}} & 0 & 0 & c_{14} \end{pmatrix}$$
$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{23} & s_{23} & 0 \\ 0 & -s_{23} & c_{23} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{13}} & 0 \\ 0 & 1 & 0 & 0 \\ -s_{13}e^{i\delta_{13}} & 0 & c_{13} & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 & 0 \\ -s_{12} & c_{12} & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

where $c_{ij} = \cos\theta_{ij}$ and $s_{ij} = \sin\theta_{ij}$, with $\theta_{ij} \in [0, \pi/2]$, $\delta_{ij} \in [0, 2\pi]$.

Parameterisation II

$$V = A_L^\dagger = \left(\begin{array}{ccc} c_{12}\, c_{13}\, c_{14} & s_{12}\, c_{13}\, c_{14} & s_{13}\, c_{14}\, e^{-i\delta_{13}} \\ \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots \\ \hdashline \cdots & \cdots & \cdots \end{array}\right) \equiv \left(\begin{array}{c} K_{\text{CKM}} \\ \hdashline K_T \end{array}\right)$$

In the weak basis where down quarks are diagonal.

$$K_{\text{CKM}} = H_L\, U_{\text{CKM}} \equiv (\mathbb{1} - \eta)\, U_{\text{CKM}}$$

Parameterisation III

$$F^u = \left(\begin{array}{c:c} K_{\text{CKM}} K_{\text{CKM}}^\dagger & K_{\text{CKM}} K_T^\dagger \\ \hdashline K_T K_{\text{CKM}}^\dagger & K_T K_T^\dagger \end{array}\right)$$

$$= \begin{pmatrix} 1-\Delta_1 & -\sqrt{\Delta_1}\sqrt{\Delta_2}e^{-i(\delta_{14}-\delta_{24})} & -\sqrt{\Delta_1}\sqrt{\Delta_3}e^{-i\delta_{14}} & -\sqrt{\Delta_1}e^{-i\delta_{14}} \\ -\sqrt{\Delta_1}\sqrt{\Delta_2}e^{i(\delta_{14}-\delta_{24})} & 1-\Delta_2 & -\sqrt{\Delta_2}\sqrt{\Delta_3}e^{-i\delta_{24}} & -\sqrt{\Delta_2}e^{-i\delta_{24}} \\ -\sqrt{\Delta_1}\sqrt{\Delta_3}e^{i\delta_{14}} & -\sqrt{\Delta_2}\sqrt{\Delta_3}e^{i\delta_{24}} & 1-\Delta_3 & -\sqrt{\Delta_3} \\ -\sqrt{\Delta_1}e^{i\delta_{14}} & -\sqrt{\Delta_2}e^{i\delta_{24}} & -\sqrt{\Delta_3} & \Delta_1+\Delta_2+\Delta_3 \end{pmatrix}$$

New Physics

New Physics

- D^0-$\overline{D}^0$ (tree level)
- K^0-$\overline{K}^0$ (loop)
- $B^0_{d,s}$-$\overline{B}^0_{d,s}$ (loop)
- CP violation in $K_L \to \pi\pi$
- Rare top decays $t \to (u, c)Z$

Conservative estimate: NP $<$ Exp

New Physics II

We used this to restrain our fit, for instance

Observable	$m_T = 1\,\mathrm{TeV}$	$m_T = 3\,\mathrm{TeV}$
Δm_K	$\lvert V_{Td}\rvert\lvert V_{Ts}\rvert < 7.4\times10^{-4}$	$\lvert V_{Td}\rvert\lvert V_{Ts}\rvert < 2.7\times10^{-4}$
Δm_B	$\lvert V_{Td}\rvert\lvert V_{Tb}\rvert < 6.7\times10^{-4}$	$\lvert V_{Td}\rvert\lvert V_{Tb}\rvert < 3.4\times10^{-4}$
Δm_{B_s}	$\lvert V_{Ts}\rvert\lvert V_{Tb}\rvert < 3.2\times10^{-3}$	$\lvert V_{Ts}\rvert\lvert V_{Tb}\rvert < 1.6\times10^{-3}$
$\lvert\epsilon_K\rvert$	$\lvert V_{Td}\rvert\lvert V_{Ts}\rvert\sqrt{\lvert\sin 2\Theta\rvert} < 8.8\times10^{-5}$	$\lvert V_{Td}\rvert\lvert V_{Ts}\rvert\sqrt{\lvert\sin 2\Theta\rvert} < 3.1\times10^{-5}$

where $\Theta = Arg(V_{Ts}^{*}V_{Td})$
The mass dependence on the bounds comes from the Inami-Lim loop functions.

Perturbativity

$$\mathrm{Tr}\left(mm^\dagger + \overline{m}\,\overline{m}^\dagger\right) = p\ m_t^2$$

$$\mathrm{Tr}\left(mm^\dagger + \overline{m}\,\overline{m}^\dagger\right)\ \simeq\ m_t^2 + \left(\Delta_1 + \Delta_2 + \Delta_3\right) m_T^2$$

$$\sqrt{\Delta_1 + \Delta_2 + \Delta_3} = \sqrt{p-1}\ \frac{m_t}{m_T}$$

For $\Delta \equiv \Delta_1 \gg \Delta_2 \sim \Delta_3$ and since $\sqrt{p-1}$ should be $O(1)$

$$m_T \lesssim \frac{m_t}{\sqrt{\Delta}}$$

Fit

Procedure

- NP + Perturbativity to restrict parameter space
- Best fit region minimizing

$$\chi^2 = \sum_{ij} \left(\frac{V_{ij} - V_{ij}^c}{\sigma(V_{ij})} \right)^2 + \left(\frac{\gamma - \gamma^c}{\sigma(\gamma)} \right)^2$$

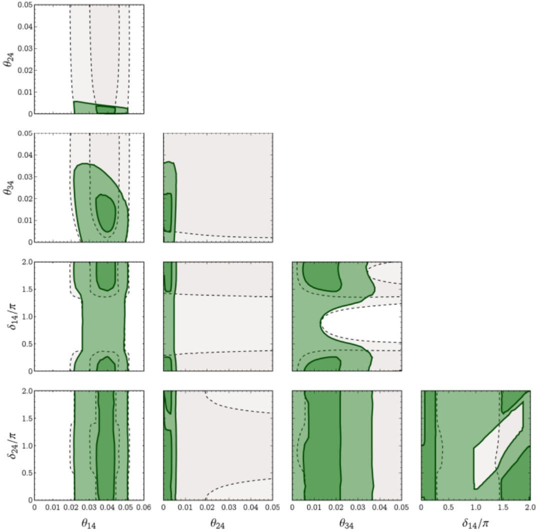
Fit II

Using best-fit values of *CKM* without imposing unitarity, V^c_{ij} is given by

$$|K_{\mathrm{CKM}}| = \begin{pmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & (3.82 \pm 0.24) \times 10^{-3} \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & (41.0 \pm 1.4) \times 10^{-3} \\ (8.0 \pm 0.3) \times 10^{-3} & (38.8 \pm 1.1) \times 10^{-3} & 1.013 \pm 0.030 \end{pmatrix}$$

And $\gamma^c = (72.1^{+4.1}_{-4.5})^\circ$, since the presence of an up-type VLQ does not affect the value of the phase $\gamma = \arg(-V_{ud}V_{cb}V^*_{ub}V^*_{cd})$, which is obtained from SM tree-level dominated B decays.

Results



0.05
0.04
0.03
0.02
0.01
0
θ_{24}
θ_{34}
2.0
1.5
1.0
0.5
δ_{14}/π
δ_{24}/π
0 0.01 0.02 0.03 0.04 0.05 0.06
θ_{14}
0 0.01 0.02 0.03 0.04 0.05
θ_{24}
0 0.01 0.02 0.03 0.04 0.05
θ_{34}
0 0.5 1.0 1.5 2.0
δ_{14}/π

Results II

The selected point in parameter space corresponds to a mass $m_T = 1.5$ TeV and is described by

$$\theta_{12} = 0.2265 \ , \quad \theta_{13} = 0.003818 \ , \ \theta_{23} = 0.03998 \ ,$$

$$\theta_{14} \simeq \sqrt{\Delta_{(1)}} = 0.03951 \ , \quad \theta_{24} \simeq \sqrt{\Delta_2} = 0.002078 \ , \quad \theta_{34} \simeq \sqrt{\Delta_3} = 0.01271 \ ,$$

$$\delta_{13} = 0.396\,\pi \ , \quad \delta_{14} = 1.818\,\pi \ , \quad \delta_{24} = 0.728\,\pi \, ,$$

corresponding to $\chi^2 \simeq 3.2$, to a perturbativity factor $p - 1 \simeq 0.13$.

Results III

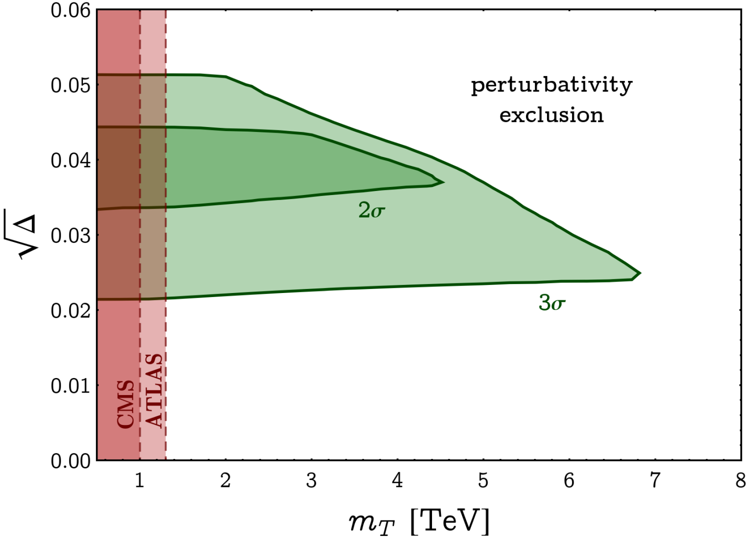
$$|\mathcal{V}_L^\dagger| \simeq \begin{pmatrix} 0.9737 & 0.2243 & 0.0038 & 0.0395 \\ 0.2243 & 0.9737 & 0.0400 & 0.0021 \\ 0.0081 & 0.0393 & 0.9991 & 0.0127 \\ 0.0390 & 0.0065 & 0.0126 & 0.9991 \end{pmatrix}$$

Results IV

$$|F^u| = \begin{pmatrix} 0.99843969 & 0.00008203 & 0.00050179 & 0.03946672 \\ 0.00008203 & 0.99999569 & 0.00002638 & 0.00207496 \\ 0.00050179 & 0.00002638 & 0.99983863 & 0.01269224 \\ 0.03946672 & 0.00207496 & 0.01269224 & 0.001726 \end{pmatrix}$$

$$|\eta| = \begin{pmatrix} 0.78016 & 0.04102 & 0.25089 \\ 0.04102 & 0.00216 & 0.01319 \\ 0.25089 & 0.01319 & 0.08069 \end{pmatrix} \times 10^{-3}$$

Results V


0.06
0.05
0.04
0.03
0.02
0.01
0.00
1
2
3
4
5
6
7
8
m_T [TeV]
$\sqrt{\Delta}$
perturbativity exclusion
2σ
3σ
CMS
ATLAS

Future Work

A Review on VLQs, in collaboration with J. M. Alves, A.L. Cherchiglia and C.C. Nishi.

Conclusions

- DUs might play an important part in the discovery of New Physics.
- DUs can be the bridge to new heavy particles that might explain current anomalies.
- Vector-like quarks are one of the simplest solutions available.

The End

Thank You!