Aspects of Models with Vector-Like Singlet Quarks

- Works done in collaboration with Francisco Albergaria, J. Alves, José Filipe Bastos, Francisco Botella, G.
- arXiv: 2307.13073; arXiv: 2103.13409, JHEP07 (2021)099; arXiv: 2111.15402, Eur Phys J. C. 82

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(2022) 4, 360; arXiv: [2304.10561,](https://arxiv.org/abs/2304.10561) [Vector-like Singlet Quarks: a Roadmap](https://inspirehep.net/literature/2653355)

- **G. C. Branco CFTP-ULisboa, IST**
	- **Talk given at**

- **Workshop on the Standard Model and Beyond**
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Vector-like fermions arise for instance in grand unified models

Possible motivations to introduce isosinglet vector-like quarks

Naturally small violation of 3x3 unitarity of the VCKM and non-vanishing but naturally suppressed flavour-changing n (FCNC)

This opens up many interesting possibilities for rare K and B decays as well as CP asymmetries in neutral B de

Adding isosinglet quarks to the SM leads to new sources of CP violation

In particular one may achieve spontaneous CP violation in this framework with the addition of a complex scalar singlet to the Higgs sector

Possibility of solving the strong CP problem a la Barr and Nelson

Bento, Branco, Parada, 1991

Possibility of having a Common Origin for all CP Violations

Branco, Parada, MNR, 2003

Fundamental properties of the CKM matrix r dinadimonical proportios of the Cryprinati*n* Eundamental properties of the CKM **n** .
ا *L* charged currents in the quark sector: α in the quark sector: α

G. C Branco, L. Lavoura, J. P. Silva "CP Violation" Oxford University Press 1999 $C E$ *S*ranco, L. Lavou ra, J<mark>.</mark> P. *d* G. C Branco, L. Lavoura, J. P. Silva "CP Violation" Oxford University Press 1999

^k . (3.19) There is freedom to rephase the mass eigenstate quark fields. As a result: Under this representation of the control of the co
Under the control of the control of

The CKM matrix is complex, but some of its phases have no physical meaning. This is due to the *^k .* (3.19) biz **de la component de la com** \mathbf{u}_k

$$
\mathscr{L}_{\text{CC}} = \left(\overline{u} \,\,\overline{c} \,\,\overline{t}\right)_L \gamma^{\mu} \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L W^+_{\mu} + \text{H.c.}
$$

The CKM matrix is complex but not all its phases have physical meaning Fhe CKM matrix is complex but not all its phases have physical n \overline{c} α all its phases have physical

$$
u_{\alpha} = e^{i \varphi_{\alpha}} u'_{\alpha}, \qquad d_k = e^{i \varphi_k} d'_k
$$

$$
V'_{\alpha k} = e^{i(\varphi_k - \varphi_{\alpha})} V_{\alpha k}
$$

It is consequent in the individual phase in the individual phases of *Only rephasing* **invariant quantities have physical meaning.** The simplest rephasing invariants of the CKM matrix are moduli and "quartets" It is a clear from equal phases of the *CVM* metrics one and the nod law entertail the employ rephasing invariante of the similarity are media and quartete Only rephasing invariant quantities have physical meaning. The simplest rephasing invariants of the CKM matrix are moduli and "quartets" the simplest rephasing invariants of the GKM matrix are moduli and quartets. Only rephasing invariant quantities h
The simplest rephasing invariants of the CKM examples are moduli *|V*a*k|* and quartets *Q*a*i*^b *^j*, defined as

$$
|V_{\alpha k}| \tQ_{\alpha i \beta j} \equiv V_{\alpha i} V_{\beta j} V_{\alpha j}^* V_{\beta i}^* \t\text{with } \alpha \neq \beta \text{ and } i \neq j.
$$

Higher order Invariants can in general be written in terms of these. *Q*a*i*^b *^j* ⌘ *V*a*iV*^b *jV*⇤ ^a *jV*⇤ ^b*ⁱ ,* (3.21) *Cai*b *j l y die di De Written in terms of* Higher order Invariants can in general be written in terms of these .

Gui: GUI ABC: ABCDEFGHIJKLMNOPQRSTUVWXYZ $\overline{}$

Details about Rephasing invariant quantities Gui: GUI abc: ahk about Repria abc:
Dataile ahout

\blacksquare **Example :** \qquad $Q = V_{us}V_{cb}V_{cs}^*V_{ub}^*$ $\text{Im } Q \cong \text{HAG}(\text{Sing of } Q)$ *csV* ⇤ *ub* $Im Q \Delta$ m_0 α

is essentially the pine of the Cabibbo angle and it is a parameter appearing in the Wolfenstein parametrisation of the CKM matrix "ט
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ari of the Cabibbo angle and it is a parameter Instein parametrisation of the CKM matrix $\frac{1}{2}$ exine of the C
Molfenstein p

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abc: A hk
bout Rephasing invariant quantities α δ hasing invariant quantities Guitar Card and an
Guitar \ln k $\frac{1}{2}$ variant quantities abc: ahk $\overline{}$ $\overline{}$ Δ \ln $\frac{1}{2}$ mivariant qua abc: Ahk

 $\alpha = \alpha \sin(\omega t)$ $Q = V_{us}V_{cb}V_{cs}^*V_{ub}^*$ $Q = V_{us}V_{cb}V_{cs}^*V_{ub}^*$ ω 5 ω 6 ω 18 $\frac{uv}{V^*V^*}$ *CS WO*
V V V W cs Im *Q* ' ⁶ sin(arg *Q*) $\text{Lmg@}_{\text{mTarb}}\lambda^6$ $\sin(\arg Q)$

Ilm QI has the same value for all quartets and measures the strength of CP violation in the SM. the strength of CP violation in the SM.

is of order 1

In the SM, one can show that all imaginary parts of rephasing invariant quartets: *V*a*iV*^b *jV*g*kV*⇤ ^a *jV*⇤ b*kV*⇤ ^g*ⁱ* = *|V*b*i|* 2 . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.
2 . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3.22) . (3. **Example 19 The SM, one 1** the SM, one can show

, (3.23) In the SM, neutrinos are exactly massless. No Dirac mass terms can be written since right-

Differences between the imaginary parts of the quartets *Flavour Physics and CP Violation in the SM and Beyond* B e_c *Vifferences betwe* $\frac{1}{2}$ *,* (3.23)

$$
V_{us}V_{cb}V_{ub}^*V_{cs}^* = Q_{uscl}
$$

erent result, for example: In the presence of VLQs one obtains a different result, for example: In the presence of VLQs one obtains a different result, for example:

 $3.0 \quad 1 \quad \Omega$ $Im Q$ 2112 - $Im Q$ 1132 = $Im Q$ 1142 massless neutrinos, neutrinos, neutrinos, neutrinos, neutrinos, neutrinos, neutrinos, neutrinos, neutrinos, ne
Altres neutrinos, neutrinos, neutrinos, neutrinos, neutrinos, neutrinos, neutrinos, neutrinos, neutrinos, neut $\begin{array}{ccc} \n\hline\n\end{array}$ handed introduced introduced introduced in the other hand, Majorana mass terms are not in the other hand, Majorana mass terms are not intervals of \sim Im Q_2112 - Im Q_1132 = Im Q_1142

$$
V_{cd}V_{ts}V_{td}^*V_{cs}^* = Q_{cdt}
$$

a.
1 Neutrino massessing massessing massessing massessing massessing massessing massessing massessing massessing m have the same modulus

Changes in the unitarity relations in the presence of VLQs

In the SM, 3x3 unitarity of the CKM matrix leads to an "asymmetry" and and only defined as:
In the only defined as: \overline{y} the Cr <u>IVI matrix leads</u> to an asymmetry

Moduli differences:

$$
\mathbf{a} \equiv |V_{31}|^2 - |V_{13}|^2 = |V_{23}|^2 - |V_{32}|^2 = |V_{12}|^2 - |V_{21}|^2
$$

 $\frac{1}{2}$ In an SM extension with one up-type VLQ the quark mixing matrix consists of the first three columns of a 4x4 unitary matrix: In an SM extension with one up-type VLQ the quark mixing matrix consists of the first three columns of a 4x4 unitary matrix: In an Sivi extension with one up-type vily the

$$
V = \begin{pmatrix} V_{11} & V_{12} & V_{13} & V_{14} \\ V_{21} & V_{22} & V_{23} & V_{24} \\ V_{31} & V_{32} & V_{33} & V_{34} \\ V_{41} & V_{42} & V_{43} & V_{44} \end{pmatrix}
$$

Albergaria, gcb, 2023

Using unitarity of other rows and columns of V one obtains: Applying a similar procedure using the unitarity relations of the other rows and columns of V , we

Changes in the unitarity relations in the presence of VLQs Frangoo in the annanty rolations in the procence of the ne unitarity relations in the presence of VLQs ² = 1. (5b)

$$
^2 < (2.1 \pm 1.2) \times 10^{-8}.
$$

 $,$ \bullet

|V11| ² ⁺ [|]V21[|] ² ⁺ [|]V31[|] ² ⁺ [|]V41[|] ² = 1. (5b) I row and first column of V, one derives: From unitarity of first row and first column of V, one derives: |V11| ² ⁺ [|]V21[|] ² ⁺ [|]V31[|] ² ⁺ [|]V41[|]

$$
a_{12,13} \equiv (|V_{12}|^2 - |V_{21}|^2) - (|V_{31}|^2 - |V_{13}|^2) = |V_{41}|^2 - |V_{14}|^2
$$

$$
a_{12,32} \equiv (|V_{12}|^2 - |V_{21}|^2) - (|V_{23}|^2 - |V_{32}|^2) = |V_{24}|^2 - |V_{42}|^2,
$$

\n
$$
a_{13,23} \equiv (|V_{13}|^2 - |V_{31}|^2) - (|V_{32}|^2 - |V_{23}|^2) = |V_{34}|^2 - |V_{43}|^2.
$$

From $D_0 - \overline{D_0}$ mixing, we know that, in models with one up-type VLQ, we have $|V_{14}|^2 |V_{24}|^2 < (2.1 \pm 1.2) \times 1$ From $D_0 - D_0$ mixing, we know that, in models with one up-type VLQ, we have $[9]$ $|V_{14}|$ 2 $|V_{24}|$ $\frac{1}{2}$

 \mathbf{R} . (a) \mathbf{R}

In the SM it is not possible to generate the Baryon Asymmetry of the Universe (BAU) \mathbf{F} is the \mathbf{M} in the value of the \mathbf{F} violation there is \mathbf{F} or violation, even in the \mathbf{F} ill the SM it is not possible to generate the Dai
Limit are an in $\mathcal{L}(\mathcal{$ not possible to generate the Baryon As \mathcal{F} , the diagonalized up-type quark mass mass mass matrix \mathcal{F} , the diagonalized up is given by \mathcal{F}

$$
\mathcal{I}_{\mathrm{CP}} = \mathrm{tr}[y_uy_u^\dagger,y_dy_d^\dagger]^3
$$

where you are the Witch Windows may be your coupling matrices. mass matrices as y^u = OUCIS WILLI V 1 ww.commun.com
Mariante r much lower mass scale. CP-odd WBI, tr[hu, hd] $\frac{3}{3}$ In models with VLQs one may have CP odd invariants of much lower mass scale invariants of much lower mass scale

Example: Example: Frample: Example: nple:

 $\text{tr} \left(\left[h_u,h_d^s\right]H_u^{(2)}\right) \qquad \begin{array}{c} H_u^{(r)} \equiv m_u(m_u^{\dagger}m_u + h_u^{\dagger}m_u) \ h_u \equiv m_u^{\dagger} \end{array}$ $\left(\right)$

One of the reasons is that in the SM CP violation is too small:

$$
\mathcal{I}_{\rm CP} = {\rm tr}[y_u y_u^\dagger, y_d y_d^\dagger]^3 \sim \frac{{\rm tr}[h_u, h_d]^3}{v^{12}} \sim 10^{-25}
$$

$$
\mathrm{tr} \left(\left[h_u, \, h_d^s \right] H_u^{(2)} \right) \qquad H_u^{(r)} \equiv m_u (m_u^\dagger m_u + M_u^\dagger M_u)^{r-1} m_u^\dagger \nonumber \\ h_d \equiv m_d m_d^\dagger
$$

ample at the TeV scale, light fermion masses are negligible and there is no possibility of \mathbb{F}_q distinguishing light quark jets. Sizeable CP violation at high energy is expected to have i k M max x of ω ω $Y-5=4$ reflasing invariant flow 4 *Vel*taire productions of the sees extended physical physical photography on a mation was be $V =$ $|V_{ud}|$ $|V_{us}|e^{i\chi'}$ $|V_{ub}|e^{-i\gamma}|$... $-|V_{cd}|$ $|V_{cs}|$ $|V_{cb}|$ $| \cdot \cdot \cdot$ $|V_{td}|e^{-i\beta} - |V_{ts}|e^{i\chi} - |V_{tb}| - |V_{tb}|$.
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. . . .
.
. . . .
.
. V ^{V}CKM
 $\frac{1}{2}$ $\overline{}$ $V_{\rm CKM}$

. (3.30)

The phanes 8, B, B, BK are arguments of $\gamma = \arg (-V_{ud}V_{cb}V_{ub}^*V_{cd}^*)$ β = ang $(-v_{cd}v_{tb}v_{tb}^*v_{t}^*)$ $\beta_5 = \alpha \gamma_6 (-v_{cs} v_{cs} v_{cs} v_{cb}^T)$ $\beta \kappa = \arg(-V_{us}V_{cd}V_{ud}^{\pi}V_{cs}^{\pi})$ Sometimes one also introduces & = ang (Yellis Vud Yes $\alpha \equiv \pi - \beta - \delta$ By definition!!!

Within the SM, 3x3 unitarity implies some exact relations among rephasing invariant quantities: $\frac{|V_{ub}|}{|V_{td}|} = \frac{sin\beta}{sin\gamma} \frac{|V_{cb}|}{|V_{ud}|}$ $sin \beta_s = \frac{|Vtd|}{|Vts|} \frac{|V_c d|}{|V_{rs}|} sin \beta = O(\lambda^2)$ $\sin \beta_K = \frac{|V_{ab}|}{|V_{as}|} \frac{|V_{cb}|}{|V_{as}|} \sin \delta = O(\lambda^4)$

violated, $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 < 1$, at the level of two or three standard deviations. This violated, $|Vud|$ $\top |Vus|$ $\top |Vub|$ \leq 1, at the level of two of three standard deviations. This parameteris of $|v_{us}|$ and $|v_{ud}|$ indicate that unitarity
independent in the n_{si} of the or the or the *n*-th row of \mathbf{v} **V** to two day \mathbf{v} \mathbf{v} and \mathbf{v} *functions and* $|V_{us}|$ and $|V_{ud}|$ indicate that unitarity of the first row $\frac{1}{2}$ $\frac{1}{2}$

deficit results from new theory calculations of the SM radiative corrections to -decay **Experimental data suggests: Experimental confirmed in Refs. [3]. If the refs. It is referred in Refs. In Refs. it is result that the set of th** Experimental data suggests: ² *[|]Vus[|]* ² *[|]Vub[|]* 2 = 2 = *s*² **Experimental data suggests: Phys. Rev. 2006)** 2007.

$$
\Delta \, \equiv \, \Delta_1 \, = \, 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 \, = \, |{\cal V}_{L_{41}}^*|^2 \, = \, s_{14}^2
$$

B. Belfatto, R. Beradze and Z. Berezhiani, *The CKM unitarity problem: A trace* of new physics at the TeV scale?, Eur. Phys. J. C 80 (2020) 149 [1906.02714]. ⌘ ¹ = 1 *|Vud| V*
*L*_{*D D cu*ence is an i} Q ^{*l*}cd_{*i*} Q ^{*l*}_c Q ^{*l*}_c Q ^{*l*}_c Q ^{*l*}_c Q ^{*l*}_c Q _{*l*}^{*l*}_c Q _{*l*}^{*l*}cd_{*i*} \int *scale* $\widetilde{\mathcal{C}}$ $\frac{6}{3}$ of new physics at the TeV scale?, *Eur. Phys. J. C* 80 (2020) 149 [1906.02714]. [8] B. Belfatto, R. Beradze and Z. Berezhiani, *The CKM unitarity problem: A trace*

 $\Delta \, \equiv \, \Delta_1 \, = \, 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 \, = \, \left| \mathcal{V}^*_{L_{41}} \right|^2 \, = \, s^2_{14}$ are minimal and have the notable feature of leading to naturally suppressed violations $\sqrt{\Delta} \sim 0.04$ $\Delta \sim 0.04$ ² *[|]Vcb[|]* $\sqrt{\Delta} \sim 0.04$ $\frac{2}{\pi}$ – $\frac{2}{\pi}$ $\overline{\mathsf{L}}$ \boldsymbol{V} $\Delta \, \equiv \, \Delta_1 \, = \, 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 \, = \, \left| \mathcal{V}^*_{L_{41}} \right|^2 \, = \, s_{14}^2$ $\sqrt{ }$ unitarity, one can also consider the left-polar decomposition of the left-polar decomposition of the left-pola
The left-polar decomposition of the left-polar decomposition of the left-polar decomposition of the left-polar
 Cabibbo Angle Angle Andre Andre Andre Andre Angle Andre Angle Angle Angle Andre Angle Andre Angle Andre Andre A
1911. Juni 1920, *Juni 1920* | *Juli 1921.* I *LI*

RRR europertad the additional data the suggests produced the suggests produced the subject of the suggests produced the subjection of the subject o \mathcal{Q} unitarity, one can also consider the left-polar decomposition \mathcal{Y} BBB suggested the addition of a down-type (Q=-1/3) vecto *RBB* supposted the addition of a down-type $(\Omega = -1/3)$ vector-like isosingle [1912.08823].

In alternative, the introduction of an up-type (Q=2/3) vector-like isosinglet quark is especially interesting since experimental timits on FCNC in the up sector are less stringent than those **UCCAM IS AND IS A UNITARY IS A UNITED INCO AND INCO AND INCORPORATE INCONSTRUCT IS A UP AND THE MATRIX MATRIX M**
The site of a COMO in the same as a tax and has a strip mant the same that a second limits on FCNC in the up sector are less stringent than those In alternative, the introduction of an up-type (Q=2/3) vector-like

zark. Z \overline{a} in the down sector The key question addressed in this paper is whether it is possible to have the rein into on fund in the up sector are less stringent than those framework deviations from unitarity are naturally suppressed by the ratios $\frac{1}{\sqrt{2}}$ ($\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ ($\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\$ w. alternative, and analogue of our operative to the section 2. isosinglet quark is especially interesting since experimental

Recent measurements of $|V_{us}|$ and $|V_{ud}|$ indicate that unitarity of the first row may be Becent measurements of $|V|$ and $|V|$ indicate that unitarity of the first row may be reduce the standard one $\int u(s) \, du$ and $\int u(a)$ indicate the university of the institutions This

Several references include α Recently it has been supported that the addition R (α) that the addition of a dittion of a down-type (α) α) α *V*⇤ ² *[|]Vtb[|]* Javour La attice A $\frac{1}{\sqrt{2}}$.V
V eraging group) (2111. *^K*CKM ⁼ *^H^L ^U*CKM ⌘ (¹ ⌘)*U*CKM *,* (2.10) *GeV Mass Range*, *Phys. Rev. D* 100 (2019) 073011 [1909.11198]. Several references in our work, e.g, FLAG Review 2021 (Flavour Lattice Averaging group) (2111.09849)

BBB suggested the addition of a down-type (Q=-1/3) vector-like isosinglet quark deviations from unitarity in the first row of the first row of the first row of the CKM can alternatively be e
In the first row of the CKM can alternatively be explained by explained by explained by the can alternatively ion of a down-type (Q=-1/3) vector-like isosinglet quark BBB suggested the addition of a down-type (Q=-1/3) vector-like isosinglet quark

² *Y* for the up-type quarks, with *v* ' 246 GeV. Together with *M* and *M*, CCCA *.* (2.3) $T_P⁰$ $-h.c.$ *Ri* (*i, j* = 1*,* 2*,* 3) denote the SM quark doublets and up-type quark I_{max} we present the prospects for N_{max} to meson mixing, indirect CP violation in *K^L* ! ⇡⇡ as well as rare top decays *t* ! *qZ* $R \times 4$

(artificial splitting of R-handed components) same quantum numbers. matrix *m* = p *v ^L T*⁰ *^R* + h.c. *,* where $\frac{1}{2}$ are the SM $\frac{1}{2}$ spiltung of *H*-handed components) shows are the Milliams of Higgs doublet (α β where \mathcal{Y} are the SM Yukawa couplings, denotes the SM Yukawa couplings, denotes the Higgs doublet (\mathcal{Y} *Li* ˜*T*⁰

$$
-\mathcal{L} \supset \left(\overline{u}_L^0 \quad \overline{T}_L^0\right) \mathcal{M}_u \begin{pmatrix} u_R^0 \\ T_R^0 \end{pmatrix} + \overline{d}_L^0 \mathcal{M}_d d_R^0 + \text{h.c.}
$$

$$
m = \frac{v}{\sqrt{2}} Y^u \qquad \overline{m} = \frac{v}{\sqrt{2}} \overline{Y} \qquad v \simeq 246 \text{ GeV}
$$

$$
3 \times 3 \qquad 3 \times 1
$$

Let us to the verture of the contribution of the contribution ⇣ **u** *L* **D V D Where** with and the matrix is real diagonal transformations (the distribution of the distribution of the distribution of the matrix is real diagonal transformation of the matrix is real diagonal to the matrix of the matrix is real dia <u>၁</u> *L u* ... **Possible to choose WB where the dow** ² *Y* for the up-type quarks, with *v* ' 246 GeV. Together with *M* and *M*, *T*0

Yukawa terms and bare mass terms (notation): \tilde{P} *Terms* (notation): Yukawa terms and bare mass terms (notation): mass terms. (notation), Lagrangian is simply *L^d* ⁼ *^Y ^d* **R**, which the *R*, which the triplet under the *R*, which the *R*, which the *SU(3)* contributions in the *SU(3)* contributions in the *SU(3)* contributions in the *R* Turnared. The Small section of the Small sector relevant part of the relevant part of the Lagrangian reads, in rms and bare mass terms (notation); The SM scalar sector remains unchanged. The relevant part of the Lagrangian relevant part of the Lagrangian re We consider the SM with the minimal addition of one up-type (*Q* = +2*/*3) isosinglet Yukawa terms and bare mass terms (notation): 2 Notes and Framework and
2 Notes and Framework and
2

$$
-\mathcal{L}_u \supset Y_{ij}^u \overline{Q}_{Li}^0 \tilde{\phi} u_{Rj}^0 + \overline{Y}_i \overline{Q}_{Li}^0 \tilde{\phi} T_R^0
$$

+
$$
\overline{M}_i \overline{T}_L^0 u_{Ri}^0 + M \overline{T}_L^0 T_R^0 + \text{h.c.},
$$

(artificial splitting of R-handed components)

$$
-\mathcal{L}_d \,=\, Y^d_{ij} \,\overline{Q}^0_{Li} \,\phi\, d^0_{Rj} + \text{h.c.}
$$

Following the spontaneous breakdown of electroweak symmetry: while *M* and *M* correspond, at this level, to bare mass terms. The down-sector Yukawa Following the spontaneous breakdown of electroweak symmetry: **R** Following the spontaneous breakdown of electroweak symmetry: *Ri*, since they possess the same *i* showing the epone $$ Following the spontaneous preakdown of ele .
tr oweak : \overline{S} *Mu u*0 *R T*0 ϵ work in a weak basis (WB) where the 3 ϵ ϵ down-quark mass matrix mass ϵ down-Following the spontaneous breakdown of electroweak symmetry: while *M* and *M* correspond, at this level, to bare mass terms. The down-sector Yukawa ng the spontaneous breakdown of electroweak symmetry: Eollowing the cooptaneous breakdown of electroweak symmetry. **Lonowing the spontaneous bleakdown of electroweak syllinetry.** Following the spontaneous breakdown of electrow Following the spontaneous breakdown of electroweak symmetr *Ri* (*i, j* = 1*,* 2*,* 3) denote the SM quark doublets and up-type quark akdown of electroweak symmetry: and OWIT SHEER SYTHING U.S. SECTOR SECTION REPORT OF THE READS, INC.

$$
-\mathcal{L} \supset \left(\overline{u}_L^0 \quad \overline{T}_L^0\right) \mathcal{M}_u \begin{pmatrix} u_R \\ T_R^0 \end{pmatrix} + \overline{d}_L^0 \mathcal{M}_d d_R^0 + \text{h.c.}
$$

\n
$$
m = \frac{v}{\sqrt{2}} Y^u \qquad \overline{m} = \frac{v}{\sqrt{2}} \overline{Y} \qquad v \simeq 246 \text{ GeV} \qquad \mathcal{M}_u = \begin{pmatrix} m \\ m \\ \hline \overline{M} \\ M \end{pmatrix}
$$

\n3 × 3 3 × 1
\n
\n 4×4

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

$$
\mathcal{V}^{CKM}
$$
 corresponds to the 4×3 block of the matrix \mathcal{V}^{\dagger}

 $\mathcal{V}^{CKM} = \big($

Derema The couplings to the *Z* boson can be written as *...*

V† (4⇥3) (5) **Useful Parametrisation** F. Botella Useful Parametrisation F. Botella, L-L. Chau. 1986 USCIUI I didilictisativi F. Botella, L-L. Un tri 0 B@

$$
\mathcal{V}^\dagger = O_{34}V_{24}V_{14}\cdot V_4^{PDG}
$$

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

 Λ Λ Λ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{2}{\sqrt{2}}$ $\frac{2}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\frac{1}{\sqrt{2}}$ $\Delta \equiv \Delta_1 = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = |V_{L_{41}}^*| = s_{14}^2$ $\sqrt{\Delta} \sim 0.04$ the SM usual 3 ⇥ 3 Particle Data Group (PDG) parametrization [25] *V PDG*, and is $\sqrt{2}$ mixing, we use the $\sqrt{2}$ mixing, we use the Botella-Chau (BC) parameters of Botella-Chau (BC) parameters $\sqrt{2}$ $t_1 = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = |\mathcal{V}_{L_{41}}^*|^2 = s_{14}^2 \qquad \qquad \sqrt{\Delta} \sim 0.04$ the SM usual 3 ⇥ 3 Particle Data Group (PDG) parametrization [25] *V PDG*, and is $\Delta \equiv \Delta_1 = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = |\mathcal{V}_{lat}^*|^2 = s_{14}^2$ $\sqrt{\Delta} \sim 0.04$ $\Delta = \Delta_1$ 1 | *Particle | Particle | Particle Particle Parametrization in [25] V* Δ *V* Δ *V POII* ² = 1 *|Vcd|* $\begin{bmatrix} 1 & -1 \\ 1 & 0 \end{bmatrix}$ $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ $\begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$ ² *[|]Vts[|]* \mathcal{L} $\equiv \Delta_1 = 1 - |V_{ud}|$ $\frac{2}{\pi}$ - $\vert V \vert$ $\Omega^2 - |V_{ub}|^2 \, = \, |{\cal V}_{L_{44}}^*|^2 \, = \, 1$ *s*13*eⁱ* 0 *c*¹³ 0 $= S_{14}^2$ $\sqrt{\Delta} \sim 0.$ 0 0 10 $0²$ $= \Lambda_1 - 1 - 1$ $\Delta_1 - 1 - v$ $\sqrt{2}$ $\sqrt{2}$ $\sqrt{2}$ $\sqrt{2}$ $\sqrt{2}$ $\sqrt{2}$ $\sqrt{2}$ $|v_{us}|$ $|v_{ub}|$ $|y^*|^2 - s^2$ $\vert 1 \vert$ δ 14 $\mathbf{5}_{1}$ $=$ s_{14}^2 $\sqrt{\Delta}$ 0 0 *s*³⁴ *c*³⁴ \sim (04 0 *s*24*eⁱ*²⁴ 0 *c*²⁴ $\Delta \equiv \Delta_1 = 1 - |V_{ud}|^2 - |V_{us}|^2 - |V_{ub}|^2 = |V_{ub}|^2$ $\vert \mathcal{V}_{L_{41}}^{*}$ $\begin{array}{c} \hline \end{array}$ $\begin{array}{c} \end{array}$ $-|V_{us}|^2 - |V_{ub}|^2 \, = \, \big| {\cal V}_{L_{41}}^* \big|^2 \, = \, s_{14}^2 \qquad \quad \, \sqrt{a^2 + 4 a^2}$ $\Delta \sim 0.04$

 $\sum_{\text{C} \in \mathbb{R}^n} \mathcal{L}(K)$ and $\sum_{\text{C} \in \mathbb{R}^n} \mathcal{L}(\mathbf{C}^{\text{C}})$ and $\sum_{\text{C} \in \mathbb{R}^n} \mathcal{L}(\mathbf{C}^{\text{C}})$ V^{CKM} corresponds to the 4×3 block of the matrix V^{\dagger} V^{CKM} corresponds to the 4×3 block of the matrix V^{\dagger} \mathcal{V}^{CKM} corresponds to the 4×3 block of the matrix \mathcal{V}^{\dagger} where $\frac{1}{2}$ is the set of $\frac{1}{2}$, corresponding to the first three fir $\text{sponds to the } 4 \times 3 \text{ block of the matrix } \mathcal{V}^{\dagger}$

Non-Unitary mixing the state of the Non-Unitary mixing charged current part of the Lagrangian becomes the Lagrangian becomes the Lagrangian becomes the Lagrangian be
Charged current part of the Lagrangian becomes the Lagrangian becomes the Lagrangian becomes the Lagrangian be *l*
Willowski *u*₀
 *u*₀
 *u*₀
 *u*₀ *^µW*⁺ ary mixi *uL*↵ generality, the 3 Non-Hinitary mixing ² *^Y ^d* is diagonal. In what follows we take *^M^d* ⁼ *^D^d* = diag(*md, ms, mb*). *^VCKM* and *^F^u* ⁼ *^VCKM* $\ddot{\cdot}$ *c*¹² *c*¹³ *c*¹⁴ *s*¹² *c*¹³ *c*¹⁴ *s*¹³ *c*¹⁴ *ei*¹³

$$
\mathcal{L}_W = -\frac{g}{\sqrt{2}} \overline{u}_{Li}^0 \left(\gamma^\mu W_\mu^+\right) d_{Li}^0 = -\frac{g}{\sqrt{2}} \overline{u}_{L\alpha} \left(\gamma^\mu W_\mu^+\right) \left(\mathcal{V}^\dagger\right)^{\alpha i} d_{Li}
$$

$$
\mathcal{V}^{CKM}=\left(\mathcal{V}^{\dagger}\right)^{(4\times3)}\ =A_{L}^{\dagger}
$$

$$
\mathcal{V}^{\dagger} = O_{34}V_{24}V_{14} \cdot V_4^{PDG} \qquad V_4^{PDG} = \begin{pmatrix} \begin{bmatrix} V^{PDG} \end{bmatrix}^{(3\times3)} & 0 \\ 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}
$$

$$
\mathcal{V}_L^{\dagger} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & c_{34} & s_{34} \\ 0 & 0 & -s_{34} & c_{34} \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & c_{24} & 0 & s_{24}e^{-i\delta_{24}} \\ 0 & 0 & 1 & 0 \\ 0 & -s_{24}e^{i\delta_{24}} & 0 & c_{24} \end{pmatrix} \begin{pmatrix} c_{14} & 0 & 0 & s_{14}e^{-i\delta_{14}} \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -s_{14}e^{i\delta_{14}} & 0 & 0 & c_{14} \end{pmatrix} V_4^{PDG}
$$

K_C - . Chan 199 F. Botella, L-L. Chau. 1986

(2.6)

to zero there is no mixing with the new quark, *K*CKM is unitary and its parameterisation reduces to the standard one [38], while *K^T* = (0*,* 0*,* 0). However, it is crucial to note that

unitarity, one can also consider the left-polar decomposition

Couplings of the Z boson

$$
\mathcal{L}_Z = -\frac{g}{c_W} \left[\frac{1}{2} \left(\overline{u}_{Li}^0 \gamma^\mu u_{Li}^0 - \overline{d}_{Li}^0 \gamma^\mu d_{Li}^0 \right) \right.
$$

\n
$$
- \frac{2}{3} s_W^2 \left(\overline{u}_i^0 \gamma^\mu u_i^0 + \overline{T}^0 \gamma^\mu T^0 \right) + \frac{1}{3} s_W^2 \left(\overline{d}_i^0 \gamma^\mu d_i^0 \right) \right] Z_\mu
$$

\n
$$
\rightarrow -\frac{g}{c_W} \left[\frac{1}{2} \left(\overline{u}_L \quad \overline{T}_L \right) F^u \gamma^\mu \begin{pmatrix} u_L \\ T_L \end{pmatrix} - \frac{1}{2} \overline{d}_{Li} \gamma^\mu d_{Li} \right.
$$

\n
$$
- \frac{2}{3} s_W^2 \left(\overline{u}_i \gamma^\mu u_i + \overline{T} \gamma^\mu T \right) + \frac{1}{3} s_W^2 \left(\overline{d}_i \gamma^\mu d_i \right) \right] Z_\mu,
$$

\n
$$
F^u = A_L^\dagger A_L = 1 - B_L^\dagger B_L
$$

V **is the 41 matrix and Couplings of the Higgs boson cone finds in the charge cone of the Higgs boson of the** $\frac{1}{2}$ **. Using the cone finds in the finding eq. (2.8),** $\frac{1}{2}$ **. Couplings of the Higgs boson of the fina Couplings of the Higheral Coupling eq. (2.8)** and then in the physical basis $\mathbf C$ Couplings of the Higgs boson

$$
\mathcal{L}_h = -\frac{1}{\sqrt{2}} \overline{u}_{Li}^0 \big(Y_{ij}^u u_{Rj}^0 + \overline{Y}_i^u T_R^0 \big) h - \frac{1}{\sqrt{2}} Y_{ij}^d \overline{d}_{Li}^0 d_{Rj}^0 h + \text{h.c.}
$$

$$
\rightarrow -(\overline{u}_L \quad \overline{T}_L) F^u \mathcal{D}_u \begin{pmatrix} u_R \\ T_R \end{pmatrix} \frac{h}{v} - \overline{d}_L \mathcal{D}_d d_R \frac{h}{v} + \text{h.c.}.
$$

Let us the off-diagonal entric *H*_{X} Y Y Y Y Y Y controlled by the off-diagonal entries ν Similarly to the case of
dia Similarly to the case of *Z*-mediated FCNC, the strength of Higgs-mediated FCNC is controlled by the off-diagonal entries of the matrix F^u and by the ratios m_q/v , ($q =$ suppression – by a factor of *mu/v* or *mc/v* – is present. = u, c, t, T controlled by the off-diagonal entries of the matrix F^u and by the ratios m_q/v , (*q* = $=$ u, c, t, T

where one identifies an enlarged 4 ⇥ 3 mixing matrix *V* , corresponding to the first three

 $\Delta V = \text{diag } V_{Ts}^* V_{Td}$ for two benchmark masses of the new heavy top quark. $V = A_L^{\dagger}$ Table 2: Constraints from neutral meson observables on products of mixing matrix

 $|V_{Td}| |V_{Ts}| \sqrt{|\sin 2\Theta|} < 3.1 \times 10^{-5}$ $m_T = 3$ TeV $| < 7.4 \times 10^{-4}$ $|V_{Td}|$ $\begin{array}{c} \hline \end{array}$ $\begin{array}{c} \end{array}$ $\begin{array}{c} \hline \end{array}$ $|V_{Ts}|$ $\vert < 2.7 \times 10^{-4}$ 10^{-4} $|V_{Td}|$ $\begin{array}{c} \hline \end{array}$ $\begin{array}{c} \end{array}$ $\begin{array}{c} \hline \end{array}$ $|V_{Tb}|$ $\vert < 3.4 \times 10^{-4}$ 10^{-3} $|V_{Ts}|$ $\overline{}$ $\begin{array}{c} \end{array}$ $\begin{array}{c} \hline \end{array}$ $|V_{Tb}|$ $\vert < 1.6 \times 10^{-3}$ 9.8×10^{-5} $\overline{}$ $\begin{array}{c} \end{array}$ $\overline{}$ $|V_{Ts}|$ $\overline{}$ $\sqrt{|\sin 2\Theta|} < 3.1 \times 10^{-5}$

Table 1: Mass and mixing parameters [38] and decay constants and bag parameters [55] for the neutral meson systems with down-type valence quarks considered in section 3.2.

*VL*⁴³ (*i* = 1*,* 2). One can approximate the total decay width of the $Br(t \to uZ)_{\text{sym}} < 1.7 \times 10^{-4}$ $Br(t \to cZ)$ $\leq 2.4 \times 10^{-4}$ (95% CL) ATI 24.6 D₁($\ell \rightarrow C\ell$)_{exp} \lt 2.4 \land 10 (30/0 O_L) \sim O₁ branching ratios is set by the ATLAS collaboration, namely Br(*^t* ! *uZ*)exp *<* ¹*.*7⇥10⁴ $Br(t \to cZ)_{\rm exp} < 2.4 \times 10^{-4}$ (95% CL) As noted in section 2.4, the tree-level NP contribution to the rare decay *t* ! *qh* is $Br(t\to cZ)_{\rm SM}\sim 10^{-14}$ J. Aguilar-Saavedra, 2004 ATLAS 2018 at leading order. This is to be contrasted with the suppressed Br(*^t* ! *uZ*)SM ⇠ ¹⁰¹⁶ and $Br(t\to cZ)_{\rm SM}\sim 10^{-14}$ J. Aguilar-Saavedra, 2004 $\frac{1}{2}$ \sim 20 $Br(t\to uZ)_{\rm SM} \sim 10^{-16}$ Br($t\to cZ)_{\rm SM} \sim 10^{-14}$ J. Aguilar-Saavedra, 200 Br(*^t* ! *cZ*)SM ⇠ ¹⁰¹⁴ [65] in the SM. In the small angle approximation, one predicts $Br(t \to uZ)_{\rm exp} < 1.7 \times 10^{-4}$ $Br(t \to cZ)_{\rm exp} < 2.4 \times 10^{-4}$ (95% CL)

whio *M*² *Z m*² \sim \sim $9(0.01)$ $\frac{1}{2}$ *m*⁴ $_{\rm gles}$ $\frac{1}{\sqrt{1}}$ *m*⁶ *,* $Br(t \to q_i Z)_{NP} \simeq 0.46 \theta_{iA}^2 \theta_{iA}^2 \sim \Delta_i \Delta_3$, which for $\mathcal{O}(0.01)$ angles still exceeds the SM contribution by several orders of magnitude. $Br(t \to q_i Z)_{NP} \simeq 0.46 \theta_{i4}^2 \theta_{34}^2 \sim \Delta_i \Delta_3$, which for $\mathcal{O}(0.01)$ angles still exceeds the SM everal orders of magnitude. *L*_{*i*} Δ ₃, which for \mathcal{O}

Free level by contributions to the rare decays $t \rightarrow q h$ From the outset is constrained by the model is constrained by the entries of the entri $t\to qZ$ ⁰*.*⁹⁷³⁷⁰ *[±]* ⁰*.*00014 0*.*²²⁴⁵ *[±]* ⁰*.*0008 (3*.*⁸² *[±]* ⁰*.*24) ⇥ ¹⁰³ suppressed with respect to *t* ! *qZ* and is not considered in our analysis. The same goes are suppressed with respect to $t\to qZ$ *t* ! *q*, which generically exceed the GIM-suppressed SM contributions. $f(x) = \frac{1}{2}$ and $\frac{1}{2}$ depends on the rare to the rare to $\frac{1}{2}$ $\frac{1}{2}$ ϵ suppressed with respect to $t\to qZ$ for the new contributions to the ratios m_a/v are suppressed with respect to $\iota \to qZ$

 m_q/v (8*.*⁰ *[±]* ⁰*.*3) ⇥ ¹⁰³ (38*.*⁸ *[±]* ¹*.*1) ⇥ ¹⁰³ ¹*.*⁰¹³ *[±]* ⁰*.*⁰³⁰

contribution between on the strongest bound of magnitude. At present, the strongest bound on the strongest chc rare decaye \pm \sqrt{a} $\frac{q}{r}$. Which generically extended the GIM-suppression $\frac{q}{r}$

$$
Br(t \to uZ)_{\rm SM} \sim 10^{-16}
$$

 $Br(t \rightarrow q_i Z)$ $v_{\rm p} \sim 0.46$ \overline{a} \overline{a} $\frac{1}{4}\,\theta_{34}^2\,\sim\,\Delta$ $\overline{\Lambda}$ *m*² \mathcal{L} $\frac{1}{2}$ β ${\rm Br}(t\,\to\,q_i Z)_{\rm NP}\,\simeq\,0.46\,\theta_{i4}^2\,\theta_3^2$ contribution by several orders of magnitude. $Br(t \rightarrow q_i Z)$ $)_{\rm N}$ *^h* ¹ .40*0*
veral $\frac{1}{4} \theta_{34}^2$ $\frac{2}{34}$ \sim 0
10

$$
Br(t \to uZ)_{\rm exp} < 1.7 \times 10^{-4}
$$
 Br(

 T ree level NP contributions to the rare decays $\begin{array}{ccc} t&\backslash &ab \end{array}$ Tree level NP contributions to the rare decays $\qquad t\,\rightarrow\,qh$ and Br t is the state of the state of $t \rightarrow a h$. e le' *v P* contributions to th + h.c. *.*

$$
\mathrm{Br}(t\to q_i Z)_{\mathrm{NP}}\,\simeq\,\frac{\left| \mathcal{V}^*_{L_{44}}\mathcal{V}_{L_{43}}\right|^2}{2\left|V_{tb}\right|^2}\,\bigg(1-\frac{M_Z^2}{m_t^2}\bigg)^2\bigg(1+2\frac{M_Z^2}{m_t^2}\bigg)\,\bigg(1-3\frac{M_W^4}{m_t^4}+2\frac{M_W^6}{m_t^6}\bigg)^{-1}
$$

(*t* ! *qiZ*)NP ' *|Fu* ✓

J. Aguilar-Saavedra, 2004 \overline{a} \overline{b} \overline{b} \overline{c} \overline{d} $\overline{d$ ar-Saaved j. Ir **guilar-Saavedra, 2004** The Higgs boson **higgs boson of the Higgs boson of the Higgs boson of the Higgs boson of Among U.** Aguilar-Saavedra, 2004

Rare top decays $t \to qZ$ (leading new physics contribution is tree level)

32 *s*²

u, c, t, T). Note that for transitions involving only the lighter quarks *u* and *c*, a strong

1911
|-
| From the outset, the model is constrained by the absolute values of the entries of the $\mathcal{L}_{\mathcal{A}}$ matrix. Their present best-fit values, with imposing unitarity, are \mathcal{A}

 $\frac{1}{2}$ due to the additional suppression by the rat due to the additional suppression by the ratios due to the additional suppression by the ratios m_q/v

Results of numerical analysis From the outset, the model is constrained by the absolute values of the entries of the with the superscript *c* denoting central values and ()=4*.*5°. We take *mc*(*MZ*) = with the superscript *c* denoting central values and ()=4*.*5°. We take *mc*(*MZ*) = *,* (4.2) ncal a ralysis (*Vij*) →
2020年
→ 2020年 $\frac{1}{2}$ *ij* numerical ana *,* (4.2) (*Vij*) \overline{c} $\overline{}$ lts of numerical ar

Take CKM from PDG without assuming unitarity with the superscript *c* denoting central values and ()=4*.*5°. We take *mc*(*MZ*) = ke CKM from PDG without assuming unitarity $\overline{}$ with the superscript values and α denotes a denotes and α and α are α and α are α and α are α and α are α are α are α and α are α are α are α are α and α are α are

 $|K_{\text{CKM}}|$ = $\sqrt{2}$ \overline{a} 0.97370 ± 0.00014 0.2245 ± 0.0008 $(3.82 \pm 0.24) \times 10^{-3}$ 0.221 ± 0.004 0.987 ± 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 ± 0.030 \setminus A *.* (4.1) $K_{CKM} = \begin{bmatrix} 0.221 \pm 0.004 & 0.987 \pm 0.011 & (41.0 \pm 1.4) \times 10^{-3} \end{bmatrix}$ $\left((8.0 \pm 0.3) \times 10^{-3} \right. \quad (38.8 \pm 1.1) \times 10^{-3} \qquad \quad 1.013 \pm 0.030 \qquad \right)$ $\sqrt{\Omega}$ $|K_{\rm CKM}| = \begin{bmatrix} 0.221 \pm 0.004 & 0.987 \pm 0.011 & (41.0 \pm 1.4) \times 10^{-3} \end{bmatrix}$ $\left((8.0 \pm 0.3) \times 10^{-3} \right. \quad (38.8 \pm 1.1) \times 10^{-3} \qquad 1.013 \pm 0.030 \qquad \right)$ $\begin{pmatrix} 0.97370 \pm 0.00014 & 0.2245 \pm 0.0008 & (3.82 \pm 0.24) \times 10^{-3} \\ 0.221 \pm 0.004 & 0.987 \pm 0.011 & (41.0 \pm 1.4) \times 10^{-3} \end{pmatrix}$ 0.987 ± 0.011 $(41.0 \pm 1.4) \times 10^{-3}$ $^{-3}$ $(38.8 \pm 1.1) \times 10^{-3}$ $(0.97370 \pm 0.00014 \quad 0.2245 \pm 0.0008 \quad (3.82 \pm 0.24) \times 10^{-3})$ $K_{\rm CKM} \vert = \vert \quad \quad 0.221 \pm 0.000$ $\left((8.0 \pm 0.3) \times 10^{-3} \right. \quad (38.8 \pm 1.1) \times 10^{-3} \qquad 1.013 \pm 0.030 \qquad \right)$ $(0.97370 + 0.00014 - 0.2245 + 0.0008 - (3.82 + 0.24) \times 10^{-3}$ 0.91910 ± 0.00014 0.2 $T3.0\pm 0.3)\times 10^{-3} \quad (38.8\pm 1.1)\times 10^{-3} \quad \quad 1.013\pm 0.030 \quad \ \ \, \Delta$ $(0.07370 + 0.00014 - 0.9245 + 0.0008 - (3.82 + 0.24)$ $|K_{\text{CKM}}| = \begin{pmatrix} 0.0181816 & 0.2211 & 0.022118 & \pm 0.00300 & 0.08711 & 0.0387 & \pm 0.011 & 0.0$ 30 /

Results after imposing previous constraints, and assuming that the priase **<u>Vamma remains unchanged:</u>** Results after imposing previous constraints, and assuming that the phase α \gamma remains unchanged: Are taken in the bounds on α constraints constraints constraints on *xD*, *m* α *M* (*N* $T(\frac{0.00 \pm 0.00)}{100}$ should allow impoung provious conolitanile, and to the solid green 3 and 3 contours after a and 3 contours after all the constraints from the previous sections from the previous sections from the previous sections from the previous sections from the previous sectio Results after imposing previous constraints, and assuming that the phase shown as the dashed regions in the dashed regions in the correlation plot of Figure 2. The correlation planet **Summanus** variant and a series of the contract of the contrac

 $\frac{1}{2}$ relatively large values for $\theta_{\text{max}} \propto \sqrt{\Lambda}$ and θ_{max} are preferred - relatively large values for $\theta_{14} \simeq 4$ *^s*), and *|*✏*K|* discussed in section 3 and the perturbativity bound of eq. (2.21). - relatively large values for $\theta_{14} \simeq \sqrt{\Delta}$ and θ_{34} are preferred *K*0*, B*0*, B*⁰ *s* is a periodic valued in a $\theta_{14} \simeq \sqrt{\Delta}$ and θ_{34} are preferred - relatively large values for $\theta_{14} \simeq \sqrt{\Delta}$ and θ_{34} are preferred *K*0*, B*0*, B*⁰ are taken into account. These constraints comprise the bounds on *xD*, *m^N* (*N* = are taken into account. These constraints comprise the bounds on *xD*, *m^N* (*N* = *Bly large values for* $\theta_{14} \simeq \sqrt{\Delta}$ and θ_{34} are preferred t_{total} and s_{total} are constraints from the \sqrt{A} constraints from the previous sections from the previous sections of previous sections from the previous sections of \sqrt{A} constraints from the previous sections Foldively large values for $v_{14} = v \Delta$ and v_{34} are preinted the bounds of $v_{14} = v \Delta$ and v_{34} are preint

ij (*Vij*) \sim (constraint coming from D^0 \overline{D}^0 mixing \sim loade to proference for en θ -conversely θ_{24} is compatible with zero The perturbativity constraint also restricts the algebra restricts of *m*¹ \overline{D}^0 , which are shownned for - CONVersely θ_{24} is compatic - conversely θ_{24} is compatible with zero $\ddot{\mathbf{u}}$ $\mathbf{1}$ $\ddot{\mathbf{u}}$ $\ddot{\mathbf{v}}$ $\ddot{\mathbf{u}}$ conversely θ_{24} is compatible with zero $\frac{1}{24}$ m compasses with data, which disfavour ∪34 = 0 at more than 2. Conversely, ∠24 is compatible with zero. Only with zero than 2.
Conversely, visit zero than 2. Conversely, visit zero than 2. Conversely, visit zero than 2. Conversely, visit sely θ_{24} is compatible with zero (constraint coming from D^0 - \overline{D}^0 mixing sheads to pion $\mathbf{1}$ and preferred by the preferred by $\mathbf{1}$ \sim CONVERSELY, σ_{24} is compatible with zero

✓ *^c*

^s), and *|*✏*K|* discussed in section 3 and the perturbativity bound of eq. (2.21). (10^{-3}) 10^{-3} are the constraints constraints constraints comprise the bounds on $\mathcal{D}(X)$, $\mathcal{D}(X)$

 $\frac{1}{2}$ in the data region of $\frac{1}{2}$ $\frac{1}{2}$ T - maximum value for m_T depends on the si against first-row deviations from unitarity in \mathcal{I} - maximum value for maximum value for $\ddot{}$ maximum value for

 $fivin \alpha$ α and α and α and α after α are the set of $\sqrt{2} = 0.04$, one minus $n\sigma \gtrsim 0$ and σ **taking** into account the full 3σ region of the fit, the bound become taking mo account the run so region of the mt, the bound become bound becomes *m^T* . 7 TeV. $\frac{1}{2}$ taking into account the full 3σ region of $=$ fixing $\sqrt{\Lambda}$. 0.04 and full μ of $T_{c}V$. \cdots \cdots \ddots \vee $\Delta - 0.04$, 0 *–* fixing $\sqrt{\Delta} = 0.04,$ one finds $m_T \lesssim 5$ TeV \overline{C} **m** \overline{I} **m** \overline{I} \overline{I} $\text{H}{\text{max}}$ *m* T \gtrsim 3 TeV. = 0*.*04, one finds *m^T* . 5 TeV. Taking into account the full 3 region of the fit, the nx ing $\sqrt{\Delta} = 0.04$, one finds - fixing $\sqrt{ }$ $\Delta = 0.04$, one finds $m_T \lesssim 5 \text{ TeV}$ $\overline{}$ **Thang** $\sqrt{\Delta} = 0.04$, one finds $m_T \geq 5$ TeV

For several correlation plots and a benchmark point see our work from *D*0-*D*⁰ mixing (see section 3.1). For several correlation plots and a benchmark point see our work

```
preferred
```
 $= 0$ at more than \overline{f} $d^2\Omega$ = 0 at Ω = 0 at more than Ω . - distavoured $\sigma_{34} = 0$ at filore than 20 - disfavoured $\theta_{34} = 0$ at more than 2σ *s* – disfavoured $\theta_{34} = 0$ at more than 2σ one sees that relatively larger values for both \sim disfavour \sim $\frac{1}{24}$ o to the version 20 at more than 2σ $\frac{1}{2}$ $\frac{1}{2}$ disfavoured $\sigma_{34} = 0$ at more than 20 one sees that $\theta_{34} = 0$ at more than 2σ - disfavoured $\theta_{34}=0$ at more than 2σ One sees that relatively large values for both ✓¹⁴ ' ^p

0*.*619 *±* 0*.*084 GeV, *mt*(*MZ*) = 171*.*7 *±* 3*.*0 GeV [68] and require *m^T >* 1 TeV, in line - no reason for common "wisdom" that T couples more strongly to third generation $\frac{1}{2}$ movimum value for $m -$ depends on the size of the deviations from (Constraint commig from D - D mixing the also to preference for small values) - maximum value for m_T depends on the size of the deviations from unitarity. (constraint coming from D^0 - \overline{D}^0 mixing (seads to preference for small values) "wisdom" that T couples more strongly to third generation against first-row deviations from unitarity in $\mathcal{O}(\mathcal{A})$ τ depends on the size of the deviations from unitarity. The perturbativity constraint also restricts the allowed values of *m^T* , which are shown - no reason for common wisdom that I couples more strongly to third generation m_T depends on the size of the deviations from unitarity. - no reason for common "wisdom" that T couples more strongly to third generation um value for m_{T} depends on the size of the deviations from unitarity *m^T* depends on the size of the deviations from unitarity. Fixing - maximum value for m_T depends on the size of the deviations from unitarity \sim and the preference shown for small values of the constraint community of the constraint community constraint co FICICILC IOI SIII VAIUCS)
Detropels to third generation The perturbativity constraint also restricts the allowed values of *m^T* , which are shown

taking into account the full 3σ region of the fit, the bound becomes $m_T \lesssim 7 \text{ TeV}$

 $\overline{2}$

The perturbativity constraint also restricts the allowed values of *m^T* , which are shown b. Denatio and Z. Derezmani, The Substrategy of the County work 2103.05549. very interesting work

I dentification of the Small numbers in VCKM. $|Vub|\approx 3.6\times 10^{-3}$ $|I_m Q| \approx 3\times 10^{-5}$ Q -> Rephasing invariant quartet of Virm In the SM, IIm Q | Las the same value for all quartets and gives the stringth of CP violation in the SM

The generation of |V_ub| and ImQ

from New Physics

We propose that the CKM matrix is generated from three different contributions

$$
V_{\text{CKM}}^{\text{eff}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \\ 0 & -s_{23} & c_{23} \\ \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{12} \\ 0 & c_{12} & \text{NP} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{13} & 0 \\ 0 & 0 & 1 \\ \end{pmatrix}
$$

Conjecture:

$$
M_d=\left(\begin{matrix}m_{11}^d & m_{12}^d & 0 \\ m_{21}^d & m_{22}^d & 0 \\ 0 & 0 & m_{33}^d\end{matrix}\right)
$$

It can be shown that one can obtain these patterns through the introduction of a Z_4 symmetry at the Lagrangian level

In order to implement the structure we assume that there is a basis where the down and up quark matrices take the form:

$$
M_u = \begin{pmatrix} m_{11}^u & 0 & 0 \\ 0 & m_{22}^u & m_{23}^u \\ 0 & m_{32}^u & m_{33}^u \end{pmatrix}
$$

Without the introduction of New Physics, one simply obtains a simplified and reduced CKM mixing, where

$$
V_{\text{CKM}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \\ 0 & -s_{23} & c_{23} \\ 0 & 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}c_{23} & c_{23}c_{12} & -s_{23} \\ -s_{23}s_{12} & s_{23}c_{12} & c_{23} \\ 0 & 0 & 1 \end{pmatrix}
$$

Our conjecture offers an explanation why: $|V_31| > |V_13|$!!!

 $V_{13} = 0$ also leads to vanishing CP violation

At this level one has: $|V_{31}| = |V_{12}| |V_{23}|$ and $V_{13} = 0$

$$
\mathcal{M}_u=\begin{pmatrix} 0 & 0 & 0 & m_{14} \\ 0 & m_{22} & m_{23} & m_{24}e^{i\beta} \\ 0 & m_{32}e^{i\alpha} & m_{33} & 0 \\ m_{41} & 0 & -m_{43}e^{i\delta} & M \end{pmatrix}
$$

then one can generate:

for the up and down quark mass matrices may also be obtained by imposing a discrete

$$
\left(\begin{array}{c|c}\n\sqrt{CKM} & +\circ & \text{Im }Q & +\circ \\
\hline\n\frac{dH}{dV} & \frac{dH}{dV}\n\end{array}\right)
$$

$Introducing a_num_tma_l$ VLQ, one obtains a 4×4 extended up-quark mass matrix with new elements. Let us then and assume the 4x4 up-type quark matrix to be of the form: Introduce an up-type VLQ

0.00292338 −0.0134741 0 0.000673705 0.0584675 0 $0 \qquad \qquad 0 \qquad \qquad 2.9$ \setminus \overline{a} $\begin{matrix} 0 \\ 0 \end{matrix}$ We consider the following mass matrices (in GeV, at the M^Z scale) for the down and \overline{a}

 0 53.7334 $0.59952 -6.91815 -1.250e^{-0.285i}$ $\begin{bmatrix} 0.040320 & 0 & 14.880e^{-0.036} & 1200 \end{bmatrix}$ $\mathcal{M}_u = \begin{bmatrix} 0 & 0.9992 & -0.91010 & 1.2006 \\ 0 & -0.0239936 & 172.862 & 0 \end{bmatrix}$ $\begin{pmatrix} 0.046526 & 0 & 14.886e^{-1.190i} & 1250 \end{pmatrix}$ $0 \t\t 0 \t\t 53.7334$ 0 0.59952 −6.91815 $1.250e^{-0.285i}$ $V = 0$ 0 -0.0239936 172.862 0 \setminus $\begin{array}{c} \hline \end{array}$

Mass matrices in GeV at the m_Z scale: Wass matrices in GeV at the m Z scale: Mass matrices in GeV at the m (22) Next, we present a benchmark numerical example of our model and compute the NP

0 02.9

$$
M_d = \left(\begin{array}{ccc} 0.00292338 & -0.0134741 & 0 \\ 0.000673705 & 0.0584675 & 0 \\ 0 & 0 & 2.9 \end{array}\right)
$$

 $\begin{pmatrix} 0 \\ 0 \end{pmatrix}$ $m_d = 0.003$, $m_s = 0.060$, $m_b = 2.9$, 0 0.59952 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6
5.01815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6.91815 −6 $\begin{array}{ccc} 0 & 0 & 0 \end{array}$ \overline{a} $\ddot{}$ 0.006 $m_d = 0.003$, $m_s = 0.000$, $m_b = 2.9$, $\bigg)$ 0.003, $m_s = 0.060, m_b = 2.9,$ $\begin{array}{ccc} & 0 & 0 & 0 \end{array}$

$$
\mathcal{M}_u = \begin{pmatrix} 0 & 0.0330. \\ 0 & -0.02399. \\ 0.046526 & 0 \end{pmatrix}
$$

 $m \geq 0.003$ m_{i} $-0.002 \quad m = 0.60 \quad m = 173 \quad m = 1951$ $0.004, 100C$ 0.009 10_l 10_l 10_l 1201 . $\begin{array}{ccc} 0 & 0 & 0 & 0 \end{array}$ one obtains the mass spectrum (also in GeV, at the MZ scale) \cdots , \cdots , \cdots , \cdots , \cdots , \cdots $m_u = 0.002, \;\; m_c = 0.60, \;\;\;\; m_t = 173, \;\; m_T = 1251.$

Numerical example: we consider the following mass mass matrices (in GeV, at the MZ scale) for the MZ scale \sim

K. $\frac{1}{2}$ $\lfloor r \cdot \frac{1}{\log n} \rfloor$ t
List $\begin{array}{ccc} \text{cea} & \text{cea} & \text{ceb} & -\text{b} & \text{c} \\ \text{cea} & \text{cea} & \text{ceb} & \text{c} & \text{c} \end{array}$ 0.01 0.04 0.01 $V_{\tau A}$ in $V_{\tau A}$ in $V_{\tau A}$ in $V_{\tau B}$ in GeV, at the MZ scale) md = 0.003, maximum = 0.060, mb = 2.9, m
Distribution = 2.9, mb = 2.9,

w is the 4×3 left-sub-matrix of the following full 4×4 m The CKM matrix is the 4×3 left-sub-matrix of the following full 4×4 mixing matrix

> $|\mathcal{V}| =$ $\bigg)$ $\overline{}$ 0.97354 0.224413 0.00370431 0.0429468 0.224536 0.973644 0.0399975 0.000996211 0.00833917 0.0393001 0.999192 0.00151171 0.0416344 0.0105585 0.001674 0.999076 \vert \vert 0.97354 0.224413 0.00370431 0.04294 0.224536 0.973644 0.0399975 0.00099 0.0233017 0.0303001 0.000102 0.0015 $\overline{}$

08
21 , $\sqrt{24}$

 \setminus

 $\begin{array}{c} \hline \end{array}$

These mass matrices lead to:

CP violation rephasing invariant phases are and the resulting CP violation rephasing invariant phases are

- $\gamma \equiv \arg \left(-V_{ud} V_{cb} V_{ub}^* V_{cd}^* \right) \simeq 68.0^\circ,$ $\psi = \cos(\sqrt{u}u \cdot c \cos \psi) - \cos \theta$
	- $\sin(2\beta) \equiv \sin[2 \arg(-V_{cd}V_{tb}V_{cb}^*V_{td}^*)] \simeq 0.746,$ $\frac{1}{2}$
- $\chi \equiv \arg \left(V_{ts} V_{cb} V_{cs}^* V_{tb}^* \right) \simeq 0.020,$ $\begin{array}{ccc} \begin{array}{ccc} \text{S} & \text$
- $\chi' \equiv \arg \left(-V_{cd} V_{us} V_{cs}^* V_{ud}^* \right) \simeq 5.71 \times 10^{-4}.$ γ' = arg (−V J/ V^{*}V^{*}) \sim 5.71 \times

 $I_{\rm CP} \simeq 3.00 \times 10^{-5}$.

 $V_{\text{UP}} = |{\rm Im} \, Q| \equiv |{\rm Im} \, (V_{ub} V_{cd} V_{ud}^* V_{cb}^*)|$ CP-odd invariant quantity $I_{\text{CP}} = |\text{Im}Q| \equiv |\text{Im}(V_{ub}V_{cd}V_{ud}^*V_{cb}^*)|$ \bullet

VLQs may play an important rôle VCKM unitarity problem. $|V_{us}|^2 + |V_{ud}|^2 + |V_{ub}|^2 < 1$ at the avel of 2,3 standard deviation. J. T. Penedo, Pedro Pereira, M.N. Abdul See See also nice work by Belfatto and Berezhiani

VLQs Provide a simple framework where there are (Vew Physics (NP) contributions to $B_d - \overline{B}_d$ mixing, $B_d - \overline{B}_d$ mixing and/or $\overline{D}^{\circ} - D^{\circ}$ mixing; Absorted control butions to $t \rightarrow c Z_{\mu}$ may reclive type-level contributions in models with up-type VLQs

VLQs may populate the desert between V and some higher scale (Mour?) without worsening the hierarchy problem To my knowledge, this was first empha-
sized in a paper by Pierre Ramond. "Fermions in the Desert" (talk given at Evice) Appears in Spires

Physics BSM with vector-like quarks (VLQs)

Rich variety of new Physics

Bare mass terms in the Lagrangian are allowed (as it is the case of neutrino Majorana mass terms)

Mixing of the new quarks with the SM-like quarks gives rise to: Deviations from unitarity of the VCKM

Z mediated Flavour-Changing-Neutral-Currents

Higgs mediated Flavour-Changing-Neutral-Currents

These new phenomena are suppressed by the ratio of electroweak scale and the masses of the new heavy quarks

VLQs may populate the desert between the EW and the GUT scale

without worsening the hierarchy problem

P. Ramond, 1981

Violation of some Dogmas of the Past!

There is an intriguing similarity between vector like quarks and This increases the plausibility of Vector-like quarks

right-hantded neutrinos. New Physics including

Standard Model (SM) and Neutrino . In the SM, rentrings are strictly manders No Dirac mass VR is not introduced No Majorana nous neither at tree livel nor at higher orders due to exact B-1 conservation. Therefore the SM has been ruled out by experiment. So one is led to: $V_{SM} \equiv SM+V_R$

 $LSDE$ SM+ ν_R If one follows "the rules" and
writer the most general neutrino mass Dirac mass: $g_{\mu}v\overline{\nu_{1}}\nu_{R}+hc.$ Majorana mass: MR VR C VR Since the Mojorana mass term is gauge inversiont, and can have MR SV. This leaps to the Seesan mechanism with: $m_\nu \approx \frac{(m_\nu^2)^2}{MR}$

So the Harvard Group dictated that neutrinos have no mass and the "right GUT" was SU(5) Where neutrinos are again manders du to accidental B-L conservation Kecall the talk by Murray Gell-Mann at Columbia about 50(10)...

Inportant feature of LR The Majorana mass term 1/8 CHR is SU(2), x U (1) invariant. Throughout MR can be significantly larger than V. $M_R > N$ Question: Can one have an analogous situation in the quark sector?
Annull: Yes! Vector-like quarks: QL, QR transform in the same way under SURMU) Q, QR is SU(2) x U(1) invariant

together with the gauge bosons and the leptons, where is a Higgs doublet and *S* is a D is a down-type vector-like quark, S is a scalar singlet to be CP invariant. The model resembles the one described in subsection 7.1, the field to be CP invariant. The model resembles the model resembles the one described in subsection \mathcal{L} D is a down-type vector-like quark, S is a scalar singlet D is a down-type vector-like quark, S is a scalar singlet

A Z_2 symmetry is imposed in order to naturally suppress a strong CP a la Barr and Nelson. trivially and all new fields (*D*⁰ *^L*, *D*⁰ transformation of the leptonic fields under the additional *Z*² symmetry be defined. The A Z_2 symmetry is imposed in order to naturally s d *v* suppress promp or and ban and repon-

 $T = 0$ first integration of a complex C_K $L^{\circ} \rightarrow -L^{\circ}, \quad S \rightarrow -S$ $D^0 \rightarrow -D^0$, $S \rightarrow -S$ $D^0 \rightarrow -D^0$ $S \rightarrow -S$ CP invariance is imposed at the Lagrangian level, therefore all coecients are real. The $\begin{array}{cccc} \texttt{L} & \texttt$

A Common Origin for all CP Violations of this quark with the SM-like quarks that this phase generates a complex *VCKM* matrix. proposed by Bento, Branco, Parada [17] which we will describe in detail in the next present to the down-type singlet include R $\bigcap_{i=1}^n C_i$ three rights of an original and singlets of a single single interactions, \mathcal{L}_1

The Lagrangian is CP invariant. CP is spontaneously violated up or down or down or down or on the number of vector-like quarks introduced.
The number of vector-like quarks introduced. The number of vector-like quarks introduced. The number of vector $\frac{1}{2}$ The Learngian is CD inverient CD in anonare electrower singlets. Larger symmetries such a symmetries symmetries such as well. The symmetries symmetries such as well. section. This **Z**² was also used recently in [90] to define VLQ of Nelson-Barr type that are electroweak singlets. Larger symmetries such **Z***ⁿ* or U(1) can be used [87] as well. following mass terms after spontaneous symmetry breakdown:

Field content, Higgs and quark sector: ⌫0 *Lm*⌫⁰ *^R* + t, $\frac{1}{2}$

$$
\left(\begin{array}{c}u^{0} \\ d^{0}\end{array}\right)_{iL}, u^{0}_{iR}, \quad d^{0}_{\alpha R}, \quad D^{0}_{L}, \quad i=1,2,3, \quad \alpha = 1,...,4, \quad \phi, \quad S
$$

proposed by Bento, Branco, Parada [17] which we will describe in detail in the next

 α r t (α) α ¹ $L^{\frac{1}{2}}(0)$, $L^{\frac{1}{2}}(1)$, $L^{\frac{1}{2}}(2)$ is not an *i* 0. 1 ii 1 iii 1 iii 1 iii 1 iii 1 iii 1 iii 1 ii 1 ⁰ denotes the left handed lepton doublets, *e*⁰ $SU(2) \times U(1) \times Z_2$ invariant $SII(2) \times II(1) \times Z_2$ invariant scalar potential $SU(2) \times U(1) \times Z_2$ invariant scalar potential potential:

> $V = V_0 (\phi, S) + (\mu^2 + \lambda_1 S^*S + \lambda_2 \phi^{\dagger} \phi)(S^2 + S^{*2}) + \lambda_3 (S^4 + S^{*4})$ $)$ $V_0 (\phi, S) + (\mu^2 + \lambda_1 S^* S + \lambda_2 \phi^* \phi)(S^2 + S^{*2}) + \lambda_3 (S^4 + S^{*4})$

 $\begin{array}{c} \textbf{D.} \\ \textbf{D.} \textbf{A.} \end{array}$ ned to connect the operation of the single since it is associated to the vertex of the vertex of the vertex of Real coefficients spontaneous CP violation

 V_0 contains all terms that are phase independent and includes the SM all SM fields are invariant under the initial *Z*² symmetry and this remains for the new where V contains all terms that are phase independent and includes the SM Higgs po- α Higgs po- α $\frac{1}{1}$ that is defined that is general that in general the version $\frac{1}{1}$ sponta-discrete $\frac{1}{1}$ V_0 contains all terms that are phase independent and includes the SM Higgs are odd and all other fields are even, as a result the two di↵erent mass scales are the vevs

tential. It was shown in Ref. [61] that in Ref. [61] that in general the vers of Eq. (7.2) violate CP sponta-
It was shown in general the vers of Eq. (7.2) via the vers of Eq. (7.2) via the vers of Eq. (7.2) via the vers

Real coefficients spontaneous CP violation
$$
\langle \phi^0 \rangle = \frac{v}{\sqrt{2}}, \quad \langle S \rangle = \frac{V \exp(i\beta)}{\sqrt{2}}
$$

scalar potential

- Non decoupling provided the scale of the bare mass term of D does not dominate over the scale of the vev of the scalar singlet, term proportional to *V* ² where *V* is the scale of the vev of the scalar singlet and another

\overline{e} ((*m^d M^d* h s $\frac{1}{2}$ both scale dominates. From *S*, and analogously from R , one sees that the suppression of deviations of devia

$$
_{jR}^{0}
$$
) - $M_d \overline{D_L^0} D_R^0 - \sqrt{2} (f_i S + f'_i S^*) \overline{D_L^0} d_{iR}^0$ + h.c.

in quark mass matrix is now of the form: bare mass term, which is real, since the *Z*² symmetry forbids the coupling (*DLDRS*) as $i,j = 1, 2, 3$ and the down quark mass matrix is now of the form:

$$
\mathcal{M}_d = \left(\begin{array}{cc} m_d & 0 \\ \overline{M}_d & M_d \end{array} \right)
$$

C. Example 2011 Sento, gcb, Parada, 1991

$$
\mathcal{M}_d \mathcal{M}_d^\dagger \; U_L = U_L \left(\begin{array}{cc} d_d^2 \\ & D_d^2 \end{array} \right) \qquad \text{with} \qquad U_L = \left(\begin{array}{cc} K & R \\ S & T \end{array} \right)
$$

rking in the weak basis where the up quarl Working in the weak basis where the up quark mass matrix is diagonal) *M* and the *M* distribution of the choose to go to a weak basis where the weak basis where $\frac{d}{dt}$ Working in the weak basis where the up quark mass matrix is diagonal) From Eqs. (7.9, 7.11) we now obtained the UVOTKING THE $\mathsf{r}\mathsf{e}$ th *D*² ייי שי

$$
S \simeq -\frac{1}{D_d^2} (\overline{M_d} \ m_d^{\dagger}) \ K \qquad \qquad \text{where here } \overline{M_{dj}} = f_j \ V e^{i\beta} + f'_j V e^{-i\beta}
$$

$$
D_d^2 \simeq (\overline{M_d} \ \overline{M_d}^{\dagger} + M_d^2) \qquad \qquad \mathcal{H}_{eff} = m_d \ m_d^{\dagger} - \frac{1}{D_d^2} (m_d \ \overline{M_d}^{\dagger}) (\overline{M_d} \ m_d^{\dagger})
$$

- θ and the scale of the bare mass term of D rovided the scale of the bare mass term of D does Scale of the pare mass term of D does not dominate over the scale of the vev of the sca
a complex VOIZM the complex version of the scale of the scalar singlet and a
The scale of the scale of the scalar singlet and another singlet and another singlet and another singlet and - Non decoupling provided the scale of the bare mass term of D does not dominate over the scale of the vev of the scalar singlet, concerning the generation of a complex VCKM
- *Hef f* = *m^d m† ^d* ¹ *MdM† ^d U^L* = *U^L d Hef f* = *m^d m† ^d* ¹ ur (*m^d M^d*)(*M^d m† ^d*) (7.30) m unitarity irrespective of which scale dominates both scales. From *S*, and analogously from *R*, one sees that the suppression of deviations - Suppression of deviations from unitarity irrespective of which scale dominates

A Common Origin for all CP Violations new *Z*² symmetry allows for a bare mass term for the vector-like quark. Therefore, there A Common Origin for all CP Violations states in the search of electromagnesism. 2π and CP is spontaneously broken. $\overline{}$ $\overline{}$ *M^d M^d* \sim *n* are two mass scales in the scale of the scale of the search term of electroweak symmetry \sim *L^Y* = $\frac{1}{2}$ A Common Origin for all CP Violations

breaking, the scale of the vev of the new scalar singlet and the scale of the bare mass term The Yukawa interactions of the quarks are given by: (all coefficients are *The Yukawa interactions of the quarks are given by:* (all coefficien row of *M^d* are potencially complex. There is a parameter redundancy in the mass matrix breaking, the scale of the vev of the new scalar singlet and the scale of the bare mass term I he Yukawa interactions of the quarks are given by: **(all coemcients are real)** where interestions of the duark are given hypertal occupied one of (all coefficients are real)

 $\mathcal{L}_Y = \sqrt{ }$ $\overline{2}(\overline{u^0} \ \overline{d^0})^i_L(g_{ij}\phi \ d^0_{jR} \!+\! h_{ij} \tilde{\phi} \ u^0_j)$ with $(i,j = 1, 2, 3)$ and the down quark mass matrix is now of the form: $\mathcal{L}_Y = -\sqrt{}$ $\sqrt{2}$ $\mathcal{L}_Y = -\sqrt{2}(\overline{u^0} \ \overline{d^0})^i_L (g_{ij} \phi \ d^0_{jR} + h_{ij} \tilde{\phi} \ u^0_{jR}) - M_d \overline{D^0_L} \ D^0_R - \sqrt{2} (f_i \ S + f'_i \ S^*) \ \overline{D^0_L}$ with $(i,j = 1, 2, 3)$ and the down quark mass matrix is now of the form: $\mathcal{M}(\mathcal{O}(\mathcal{O}))$ and $\mathcal{M}(\mathcal{O}(\mathcal{O}))$ is the other hand in the symmetric matrix $\mathcal{M}(\mathcal{O})$ is the symmetric matrix of with $(i, j = 1, 2, 3)$ and the down quark mass matrix is now of the form: $\mathcal{L}_Y = -\sqrt{2(\overline{u^0} \ \overline{d^0})}$ $\frac{i}{\sqrt{2}}$ $\left(g_{ij}\phi\ d^0_{jR}\!+\!h_{ij}\phi\ u^0_{jR}\right)$ with $(i,j = 1, 2, 3)$ and the down qua

 $\mathcal M$

in the weak basis where the symmetry is imposed. The only contribution to $\frac{1}{2}$ is the only contribution to $\frac{1}{2}$ Diagonalisation of this mass matrix: in the weak basis where the symmetry is imposed. The only contribution to *M^d* is the SANON EXTREM EXTREM
Second the contract of the cont

Concerning strong CP violation: *M*. Interestingly, the limit in which only the bare mass of the isosinglet quark becomes $\text{Concerning strong CP}$ **Concerning strong CP violation:** Concerning strong CP violation: very large leads to an unrealistic CKM matrix, showing that an interplay between the CP Ω e is e cuire a complex vector Ω . Is enough to generate at Ω CONCENTING SHONG CF VIOIANOIT. Concerning strong CP violation that acquires a complex VEV together with at least one VLQ is enough to generate a

Thus the physical parameter is the reparameterization-invariant combination $\frac{1}{2}$ $\$ \overline{CD} \overline{D} and \overline{T} violating \blacksquare

- <u>nating</u> ↵*L r* om the ↵*R j* CD violeting term eriginating from the QCD vesuum
	-
	-
- $\bar{\theta} = \theta_{\rm QCD} \theta_{\rm weak}$ We use the basis where *Y^d* accompanies ¯*qiLdjR* and similarly for *Yu*. In the presence of ble is the combination: $\theta = \theta_{\text{QCD}} - \theta_{\text{weak}}$
- $\frac{1}{2}$ will the sum of $\frac{1}{2}$ $\frac{1}{2}$ are determined to $\frac{1}{2}$. Within the SM the electric dipole moment of the neutron which is CP, P and T violating \blacksquare **IS proportional to** θ , problem than an interest of the set of the set of the set of the Standard Γ violating Γ $\overline{\mathbf{S}}$ proportional to $\overline{\theta}$
- It is the fact that $\;\overline{\theta}.\;$ is tinv that constitutes the strong CP problem: $\;\overline{\theta}\;\leq\;10^{-10}$ is tiny that constitutes the strong CP problem: $\bar\theta\,\lesssim\,10^{-10}$ \overline{a} and antie fact that $\;\;\theta_{\cdot}\;$ is tiny that constitutes the strong CP problem: $\;\;\;\theta\;\lesssim\;10^{-10}$
	- More interestingly, the Strong CP problem is quite unique in two ways: (1) it cannot be

A Common Origin for all CP Violations connects the interaction of the *W* boson, up-type quarks and down-type quarks when the that all that with the mass equivalent in the mass equivalent form, an equivalent form, and the Violati which in turn can mix with turn can mix with the SM-like quarks. The SM-like quarks. Therefore, introducing a
The SM-like quarks are fore, introducing a scalar singlet a scalar singlet a scalar singlet and the SM-like si CP Violation in Nature. Although models that seek to experience that seek to experience the complex of the complexity of the complexity of the complexity of the complexity of the complex of the complex of the complex of th of the section of the one provided one presented on the one presented on the one presented on the last section

it is the one presented on the last section of the last section of the last section of the last section of the phase and a common Origin for all CP Violations which is the SM-like the SM-like the SM-like the SM-like singletic singl violation putting CP breaking and electroweak symmetry breaking on the same footing. A COMMON ONGIN TOR ALCH VIOLATIONS A Common Origin for all CP Violations violation putting CP breaking and electroweak symmetry breaking on the same footing. whigh induces the set α tor *^j* ^X \bigcirc *g*2

From the previous page we see that in the Bento, gcb, Parada framework a complex
CKM matrix assessed from an approximately CD vialation at a high anarmy agala CKM matrix can be generated from spontaneous CP violation at a high energy scale onio matrix can be generated from spontaneous OP violation at a night the coupling through the scale we get the scale singlet singlet singlet singlet singlet singlet singlet single does not pose a problem per se. The real problem occurs when one realizes the existence Γ rom the previous page we see that in the Dento, god, raided hands From the previous page we see that in the Bento, gcb, Parada framewor CKM matrix can be generated from spontaneous CP violation at a high ϵ For CP to be spontaneously violated it must be a good symmetry of the Lagrangian, brown include the vacuum vacuum (which we see that CKM matrix can be generated from spontaneous CP violation at a high energ Bento, gcb, Parada framework

aneous CP violation at a high en gy scale $640²$ Thus the physical parameter is the reparameterization-invariant combination

$$
\mathscr{L} \,\, \supset \,\, \theta_{\rm QCD} \frac{g_s^2}{64 \pi^2} \epsilon^{\mu\nu\alpha\beta} G^a_{\mu\nu} G^a_{\alpha\beta}
$$

The QCD Lagrangian contains a CP violating term originating from the QCD vacuum *rangian contains a CP violating term originating fror* Furthermore, $\theta_{\rm QCD}$ \overline{m} *<u>ientally</u>* w ↵*R j i* d Experimentally what is measurable is the combination: $\bar{\theta} =$ T the physical parameter is the reparameterization-invariant combination-invariant combination-invariant combination-invariant combination-invariant combination-invariant combination-invariant combination-invariant comb However, CP violation has not been observed in the strong interactions Furthermore, $\theta_{\rm QCD}$ is a free parameter $\tau_{\rm b}$ α $\Omega_{\rm D}$ problem arose from the α problem and solution is the solution inclusion in the solution in the solution in the interval of the interval of the solution in the interval of the solution in the solution in the solution in the solution in the solution L ^N μ ^o μ ¹. In fact, within the SM the electric dipole momentum the SM the electric dipole momentum μ $\theta_{\rm weak} = \arg(\det \mathcal{M}_u \times \det \mathcal{M}_d)$ **However, CP violation has not been observed in the strong interactions** The QCD Lagrangian contains a CP violating term originating from the QCD vacuum

12. An established in the inclusion is the integral point of the solution is the inclusion in the solution is the integral point of the solut a free parameter is the reparameter \mathcal{M}_d) and Barr $\frac{3}{27}$. The strong CP problem arose from the 't Hooft solution to the U(1) solution Γ violation has not been observed in the strong interactions. Furthermore, α Furthermore, $U_{\rm QCD}$ is a free parameter Experimentally what is measurable is the combination: $\bar{\theta} - \theta_{\rm com}$. supp internating, which is the dendie to the computation. The experimental on the electric dipole moment of the neutron which is **CP** F The QCD Lagrangian contains a CP violating A_n motivation for the introduction for the introduction of \mathbb{R}^n is the fact that they provide one of \mathbb{R}^n thowever, of violation has not been observed in the strong interactions Furthermore, $\theta_{\rm QCD}$ is a free parameter problem [39, 40]. An essential point of the solution is the inclusion in the Lagrangian of Experimentally what is measurable is the combination: $\qquad \qquad \theta = \theta_{\rm QCD} - \theta$ $\theta_{\text{weak}} = \text{arg}(\det M_x \times \det M_y)$ $f(x) = \frac{f(x)}{x}$, where $f(x) = \frac{f(x)}{x}$ *M*. Interestingly, the limit in which only the bare mass of the isosinglet quark becomes and we have an unrealistic Contrainst Correction of the CRM matrix, showing that an interpretational between t breaking scale and the VLQ quark masses must be present. \blacksquare t ruitiennore, $U\text{QCD}$ is a free paran Experimentally what is measurable is problem [39, 40]. An essential point of the solution is the inclusion in the Lagrangian of $\theta_{\text{weak}} = \arg(\det \mathcal{M}_u \times \det \mathcal{M}_d)$ Vithin the SNA the strain dinetermore We Lagrangian contains a CP violating term originating from the QCD vacuum ver, CP violation has not been observed in the where *M*_{*d*}, *M*_{*u*} are the full mass matrices (2.4). The full mass

 $\frac{1}{\sqrt{1-\beta}}$ is proportional to $\overline{\theta}$. **Vithin the SM the electrice within the SM and** α 1011 WITHIN THE SIVI THE BIRCITIC DIPOIR MOMENT OF THE NEUTRON WHICH IS CH, Forms $\overline{\Omega}$ $\mathbf s$ proportional to θ . $\forall i$ is proportional to $\overline{\theta}_i$ Free parameter. Experimentally, when it is the computer is the computer interest is the combination $\frac{1}{18}$ which is an angle ranging from 0 to $2^{\frac{1}{2}}$. In fact, within the SM the electric dipole momentum of α

 \mathcal{L} is the sm involves the \mathcal{L} involves the \mathcal{L} 11 is the fact that $\overline{\theta}$ is time \mathcal{L}_{max} of \mathcal{L}_{max} of \mathcal{L}_{max} and the strong situation constitution const Expedition was problem. And additional symmetry is VLQs, the previous relation generalizes to to the existence of axions. Another solution [44–46] consists of assuming that CP is a no additional symmetry is restored at Lagrangian level is restored whe The end not that bound on the electric dipole moment of the neutron requires $\frac{1}{2}$ $\frac{1$ No additional symmetry is restored at Lagrangian level is restored when **It is the fact that** θ **.** is tiny that con $\alpha = 0$ and $\alpha = 0$ and α and the set of α argument v is reasonal matrices. The set of $\alpha = 0$ The additional symmetry is restored. No additional symmetry is restored at Lagrangian level is restored when $\qquad \bar\theta = 0$

A Common Origin for all CP Violations These expressions showed that the mass of the mass of the mass of the mass of the sum of a mass of a mass of a **Strong CP** term proportional to the square of the bare mass term, as a result this mass grows with \overline{D} \overline{D} \overline{D} \overline{D} where here *Mdj* = *f^j V eⁱ* + *f*⁰ *^jV ei* and *Hef f* = *m^d m†* heavy vector-like \sim 1. The first model was proposed was propos A Gommon Origin for all GP Violations $\mathbf{S}_{\mathcal{B}}$ to guarantee $\mathbf{S}_{\mathcal{B}}$, $\mathbf{S}_{\mathcal{B}}$ at tree level it was such that these heavy $\mathbf{S}_{\mathcal{B}}$ B

Melson-Barr proposal \mathcal{G} and \mathcal{G} are the following: \mathcal{G} are

arg(det*M^d* ⇥ det *mu*). In the present framework, since CP is a symmetry imposed $\alpha \times \det m_u$. vious subsection, the sum of two componenents ✓ = ✓*QCD* ✓weak were ✓weak =

reak the SM gauge group cannot break CP and they only connect the the other hand, in what concerns the generation of a complex phase in *VCKM* from spon-1. VEVs that break the SM gauge group cannot break CP and they only connect the suppress strong CP a la Barr and Nelson. Under the new **Z**² symmetry all fields of the

reak CP spontaneously cannot break the SM gauge group and they cannot be suppression of the suppression of the suppression of α SM quark neids with the additional vLQS. 2. VEVs that break CP spontaneously cannot break the SM gauge group and they can only connect SM quark fields with the additional VLQs. $\,$

Since CP is a symmetry imposed in the Lagrangian $\qquad \theta_{QCD}=0$ try *l* imposed in the Lagrangia \mathcal{O}_k Ω_{max} Ω_{max} is a seven other increased in the seven view Ω_{max} Since CP is a s with (*i, j* = 1*,* 2*,* 3) and the down quark mass matrix is now of the form *m^d* 0

$$
\theta_{QCD}=0
$$

 $|m_u|$

$$
\theta_{\text{weak}} = \quad \textbf{0} \qquad \qquad \mathcal{M}_d = \left(\begin{array}{cc} m_d & 0 \\ \overline{M}_d & M_d \end{array} \right)
$$

- 1. VEVs that term proportional to the square mass term, as a result of the bare mass α result that α term proportional to *V* ² where *V* is the scale of the vev of the scalar singlet and another usual quark fields. I. vervs that break the sivi-gauge group cannot break Or and they only connect the usual quark fields. is the same as in the first subsection, leading to the possibility of having spontaneous These expressions show that the set of the sum of the sum of $\frac{1}{n}$ and $\frac{1}{n}$ and $\frac{1}{n}$ term proportional to *V* ² where *V* is the scale of the vev of the scalar singlet and another
- **2.** VEVs that only conne the step proportional to the square mass term of the bare mass term of the bare mass $2.$ VEVS that both scales. From *S*, and analogously from *R*, one sees that the suppression of deviations

Bento, gcb, Parada model

Bento, gcb, Parada model $V_{\rm eff}$ may be replaced by bare mass terms in condition 2.1 minutes in There is an implicit assumption that these VLQs need to mix with the SM quarks. from unitarity of *VCKM* occurs irrespective of which one of these scales dominates. On the other hand, in what concerns the generation of a complex phase in *VCKM* from spon-

$$
\mathcal{L}_Y = -\sqrt{2}(\overline{u^0} \, \overline{d^0})^i_L (g_{ij} \phi \, d^0_{jR} + h_{ij} \tilde{\phi} \, u^0_{jR}) - M_d \overline{D^0_L} \, D^0_R - \sqrt{2} (f_i \, S + f'_i \, S^*) \, \overline{D^0_L} d^0_{iR} + \text{h.c.}
$$

$$
\theta_{\text{weak}} = \arg(\det \mathcal{M}_d \times \det m_u)
$$

$$
\theta_{\text{weak}} = 0 \qquad \mathcal{M}_d = \begin{pmatrix} \frac{m_d}{M_d} & 0\\ \frac{m_d}{M_d} & M_d \end{pmatrix}
$$

spontaneous symmetry breakdown through the coupling to the scalar singlet *S*. In the The initial Z_2 symmetry is thus promoted to a Z_4 symmetry. The initial Z cymmetry is thus promoted to a Z symmetry LIIC INTUIGHT 22 Symmetry is thus promoted to a 24 symmetry The initial Z_2 symmetry is thus promoted to a Z_4 symmetry

A Common Origin for all CP Violations ones given in section 7.4. The initial *Z*² symmetry is thus promoted to a *Z*⁴ symmetry with the extending the extension of the extension of the model to the model of the model of the model of the m $\overline{\mathbf{r}}$ 2 $F \sim \mu \sim \frac{1}{2}$ $\sigma \sim \frac{1}{2}$ A Common *R* + h*.*c*.* fields that are not invariant under *Z*² transform as:

Extension to the Leptonic sector: three right handed neutrin symmetry. The Yukawa terms for the sector are the sector are the sector \mathbf{r} $\frac{1}{2}$ \overline{C} *LCM*⇤ *^Lmll R* = *n^L* + *l* 2 *LCM*⇤ *^Lmll R* Extension to the Leptonic sector: three right handed neutrinos are included

the symmetry prevents the existence of bare Majorana terms, however these are generated by the coupling *^l Gl e*⁰ *^R* + ⁰ *^l ^G*⌫ ⌫ ˜ ⁰ *^R* + $\overline{2}$ reflus the existence of bare ividjorand ten
Pounlings to the field S *R R C Spirition y* prevents the existence of pare ividjorand terms, however these are generated by the couplings to the field S $\frac{1}{2}$ spontaneous symmetry breakdown through the coupling to the scalar singlet *S*. In the the symmetry prevents the existence of bare Majorana terms, however these are generated by the couplings to the field S

deed model perticles transformined **g** ⌫⁰*^T ^R C*(*f*⌫*S* + +*f*⌫ *S*⇤)⌫⁰ *^R* + *h.c.* (7.53) existence of bare Majorana mass terms for the neutrinos, which otherwise would imply there are standard moder particles transforming non-trivi there are standard model particles transforming non-trivially under the symmetry

 ${\cal L}_l = \overline{\psi_l^0} G_l \phi \,\, e_R^0 + \overline{\psi_l^0} G_\nu \tilde \phi \,\, \nu_R^0 + \frac{1}{2} \nu_R^{0T} C (f_\nu S + + f_\nu^{\,\,\prime} S^*) \nu_R^0 + h.c.$ all coefficients are real

$$
\psi_l^0 \to i\psi_l^0, \quad e_R^0 \to ie_R^0, \quad \nu_R^0 \to i\nu_R^0
$$

 $R^{0T}C(f_{\nu}S + +f_{\nu}^{'}S^{*})\nu_{R}^{0} + h.c.$

$$
\mathcal{L}_l = \overline{\psi_l^0} G_l \phi \ e_R^0 + \overline{\psi_l^0} G_\nu \tilde{\phi} \ \nu_R^0 + \frac{1}{2} \nu_R^{0T} C (f_\nu S + + f_\nu^{\ \prime} S^*) \nu_R^0 + h.c.
$$
 all coefficients are real

Imposed symmetry: $\psi_l^0 \rightarrow i \psi_l^0, \quad e_R^0 \rightarrow i e_R^0, \quad \nu_R^0 \rightarrow i \nu_R^0$ *^l* ! *ⁱ* ⁰ *^l , e*⁰ *^R* ! *ie*⁰ *^R,* ⌫⁰ *^R* ! *ⁱ*⌫⁰ *R ,* ⁰ denotes the left handed lepton doublets, *e*⁰ *^R* and ⌫⁰ $\lambda^{(0)}$ fields are integral $i\pi^{(0)}$ supposed examples the $i\pi^{(0)}$ symmetry and $i\pi^{(0)}$ symmetry $i\pi^{(0)}$ symmetry and the new the new temperature is $i\pi^{(0)}$ γ_l says in the lepton of γ_l for γ_l , γ_l fields are not in the SM fields are not in the smalles of γ_l fields are not in the smalles of γ_l fields are not in the smalles of γ_l fields are not in the smalle

$$
\mathcal{L}_l = \overline{\psi_l^0} G_l \phi \ e_R^0 + \overline{\psi_l^0} G_\nu \tilde{\phi} \ \nu_R^0 + \frac{1}{2} \nu_R^{0T} C (f_\nu S + + f_\nu S^*) \nu_R^0 + h.c.
$$

$$
=\frac{v}{\sqrt{2}}G_{\nu}
$$

framework the heavy neutrino masses are very approximately given by the eigenvalues of chosen to be real at the same time. In this weak basis the same time. In this weak basis the decay of the heavy
In this weak basis the same time. In this weak basis the decay of the heavy of the heavy of the heavy of the h three factorizable phases, one of Dirac type and two Majorana phases. In the seesaw \mathbf{I} ² , *M^k* are the heavy neutrino masses, and *I*(*xk*) = m

A Common Origin for all CP Violations symmetry. The Yukawa terms for the Violetian

$$
\mathcal{L}_{l} = \overline{\psi_{l}^{0}} G_{l} \phi \ e_{R}^{0} + \overline{\psi_{l}^{0}} G_{\nu} \tilde{\phi} \ \nu_{R}^{0} + \frac{1}{2} \nu_{R}^{0} C (f_{\nu} S + + f_{\nu}^{\prime} S^{*}) \nu_{R}^{0} + h.c.
$$

$$
\mathcal{M} = \begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix}, \quad m_l = \frac{v}{\sqrt{2}} G_l, \quad m = \frac{v}{\sqrt{2}} G_\nu
$$

$$
M = \frac{V}{\sqrt{2}} (f_\nu^+ \cos(\alpha) + if_\nu^- \sin(\alpha)) \qquad \qquad f_\pm^\nu \equiv f_\nu \pm f_\nu'
$$

In the weak basis where m_i is to chosen to be real and diagonal light neutrino masses *d*⌫ and the low energy leptonic mixing, *UPMNS*, are obtained to an In the weak basis where m_l is to chosen to be real and diagonal *[±]* ⌘ *f*⌫ *± f*⌫ be real and diagonal to be real and diagonal

excellent approximation by: \blacksquare . In the weak basis where *m^l* is to chosen to be real and diagonal the light neutrino masses and low energy leptonic mixing are obtainable research and the low are optained to an analyzing and to analyzing and to analyzing and to analyzing and to analyzing analyzing analyzing analyzing analyz **ner** light neutrino masses and low energy leptonic mixing are obtained to an exc excellent approximation by:

$$
- K^{\dagger} m \frac{1}{M} m^T K^* = d_{\nu}
$$
 where U_{PMNS} can be identified to K

can also be generated. Possibility of having Leptogenesis can also be generated. Possibility of having Leptogenesis

Lepton number asymmetry is sensitive to the CP violating phases appearing

 $\ddot{}$ ere m_I and M are chosen to be re in the weak basis where m I and M are chosen to be real and c asymmetry given by \mathcal{I}_1 , \mathcal{I}_2 , \mathcal{I}_3 , \mathcal{I}_4 , \mathcal{I}_5 , \mathcal{I}_6 , \mathcal{I}_7 , \mathcal{I}_8 , \mathcal{I}_9 , in the weak basis where m_I and M are chosen to be real and diagonal

- approximation by. light neutrino masses and low energy leptonic mixing are obtained to an excellent approximation by: the matrix *M*. It is always possible to choose a weak basis in which both *m^l* and *M* are chosen to be real and diagonal at the same time. In this weak basis the same time. In this weak basis the decay of the heavy of the
	- can be identified to *K* = *d*⌫ *,* (6.53) where U_{PMNS} can be identified to K . as $\overline{1}$ and $\overline{2}$ $\overline{2}$ and $\overline{2}$
- m is a real matrix, while M is a generic complex matrix, therefore K will also be complex m is a real matrix, while M is a generic complex matrix, therefore K will also be complex *A^j* = *M^W* 2 *k*6=*j* Im
Imperi (*m† m*)*jk*(*m†*
- Leptonic CP violation is generated at low energies. CP violation at high energies the matrix *M*. It is always possible to choose a weak basis in which both *m^l* and *M* are framework the heavy neutrino masses are very approximately and the eigenvalues of the matrix of can also be generated. Possibility of having Leptogenesis **propriet and also be generated**. Possibility of having Leptogenesis *x* CP violation at high energie *M^j* 1 + (1 + *xk*) log(*^x^k*
- *ⁱ* (*i* = e, *µ*, ⌧) generates a lepton-number Lepton number asymmetry is sensitive to the CP violating phases appearing in $\;m^{\dagger}m\;$ Majorana neutrino *N^j* into charged leptons *l* e to the GP violating phases appe Lepton number asymmetry is sensitive to the CP violating phases appearing in m^{\dagger}
	- e real and diagonal *g*2 real, once we change to the weak basis where the matrix *M* is diagonal real and positive

$$
f_{\pm}^{\nu} \equiv f_{\nu} \pm f_{\nu}^{\ \prime}
$$

CONCLUSIONS

Vector-like quarks are very interesting candidates for physics BSM

Very simple extension of the SM, providing striking new experimental effects

- **Vector-like quarks are "cousins" of right-handed neutrinos which**
	- **provide through seesaw the most plausible explanation of the**
		- **smallness of neutrino masses**

. Weak foint: No firm frediction for the scale of VLQs. This is a universal weak point in all (so far) proposed New Physics !! The SM was an notable exception. Before gauge interactions the sugestion was TVB with $ZEGeV$! internediate vector boson...