Vector-like quarks of the Nelson-Barr mechanism

Celso C. Nishi [1]

Universidade Federal do ABC
Santo André, SP, Brazil

CFTP - Lisbon

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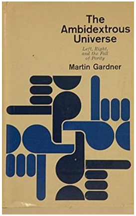
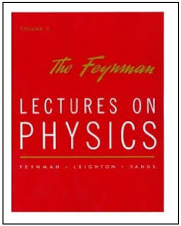
The Ozma problem



Martin Gardner '64



vol.1, Chap.51, (lectures '64)

Project Tuva (Microsoft)

Human: My heart is in the left side of my chest.
Alien: Left side?

CP is violated

***Solution** (among many): the decay is more frequent to the positron (e^+)*

$$\frac{\Gamma(K_L \to \pi^- e^+ \nu_e) - \Gamma(K_L \to \pi^+ e^- \bar{\nu}_e)}{\Gamma(K_L \to \pi^- e^+ \nu_e) + \Gamma(K_L \to \pi^+ e^- \bar{\nu}_e)} = 0.33\%$$

Fitch and Cronin, '64

'80

$K_L \to \pi\pi$

Origin in SM: complex Yukawa (qqh) couplings with one irremovable phase

$$V_{\text{CKM}} \sim \begin{pmatrix} 0.97 & 0.23 & 0.003\, e^{-i\delta} \\ 0.23 & 0.97 & 0.04 \\ 0.009 & 0.04 & 0.99 \end{pmatrix}$$

Kobayashi, Maskawa, '73

½ Nobel '08

$$J \approx \lambda^6 A^2 \eta \sim 3 \times 10^{-5}$$

one CP odd $\eta = 0.37$ is not small

The strong CP problem

- Source of CP breaking in the SM: $\bar{\theta}\, G \cdot \tilde{G} \quad \sim \mathbf{E}_a \cdot \mathbf{B}_a$
- Experimentally $\bar{\theta} \lesssim 10^{-10}$ from neutron EDM
- Theoretically $\bar{\theta}$ has two contributions: quark Yukawa + QCD
- Both could be oder one, e.g., $\delta_{\text{CKM}} \sim 66^\circ$, $\theta_{QCD} \in [0, 2\pi)$.
- Strong CP problem: Why $\bar{\theta}$ is so small?
- Technical naturalness does not apply: CP is violated in Nature.
- However, if small, radiatively stable (7 loop β in the SM).

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The strong CP problem

How to solve it?

1. Massless u quark (disfavored by lattice)
2. Promote $\bar{\theta}$ to a field $a(x)/f \to$ QCD potential $\to \langle\bar{\theta}\rangle \approx 0$ + axion
3. CP or P is a symmetry which is only spontaneously broken

The strong CP problem

3. CP or P is a symmetry which is only spontaneously broken

- Since P or CP is only spontaneously broken, $\theta_{\rm QCD} = 0$
- P is a symmetry $\rightarrow$ Left-right models

  Beg,Tsao,'78; Mohapatra,Senjanovic,'78,...

- CP is a symmetry
  - Nelson-Barr mechanism Nelson,'84; Barr,'84
  - Others

Nelson-Barr mechanism

- Arranges $\bar{\theta} = 0$ at tree level, i.e., the contribution from quark Yukawa vanishes

$$\bar{\theta}_{tree} = \theta_{\rm QCD} + \arg\det Y_d + \arg\det Y_u$$

- Large $\delta_{\rm CKM}$ should be generated
- Radiative corrections are calculable and should be tiny
- Not necessarily

Dine, Draper, JHEP, 1506.05433

The Barr criterion

SM with additional heavy VLQs (real representation) for which — Barr, PRL '84

1. Vevs that break the SM gauge group cannot break CP and they only connect the usual quark fields.
2. Vevs that break CP spontaneously cannot break the SM gauge group and they can only appear connecting SM quark fields with the additional VLQs.

Within the SM gauge group

- From 2, CP breaking scalars must be SM singlets
- Then, VLQs can only be SM copies: $B_{L,R}$, $T_{L,R}$, $Q_{L,R}$ — among 7 possible
- Doublet VLQs typically induce too large $\bar{\theta}$ — Vecchi, JHEP'17
- One H does not break CP
- With only singlet VLQs $B_{L,R}$, $T_{L,R}$, a $\mathbb{Z}_2$ is *definable* and *sufficient*

Bento-Branco-Parada model

Simplest implementation of NB

Bento, Branco, Parada, PLB'91

- Only one $\mathbb{Z}_2$ odd down-type VLQ B_L, B_R
- Only one $\mathbb{Z}_2$ odd complex scalar singlet S

$$
\begin{aligned}
-\mathcal{L} = {} & \bar{q}_{iL}\mathscr{Y}^{d}_{ij} H d_{jR} + \bar{q}_{iL}\mathscr{Y}^{u}_{ij}\tilde{H} u_{jR} \\
& + \bar{B}_L(f_j S + f'_j S^*) d_{jR} + \bar{B}_L \mathscr{M}^B B_R + h.c.,
\end{aligned}
$$

All couplings real.

$\bar{q}_L H B_R$ is forbidden

CP and $\mathbb{Z}_2$ broken by $\langle S\rangle = v_S e^{i\alpha}$.

$\langle (f_j S + f'_j S^*)\rangle = \mathscr{M}^{Bd}_j$ is an effective complex mass

The 4×4 down quark mass matrix is

$$\mathscr{M}^{d+B} = \left(\begin{array}{c|c} v\mathscr{Y}^d/\sqrt{2} & 0 \\ \hline \mathscr{M}^{Bd} & \mathscr{M}^B \end{array}\right) = \left(\begin{array}{c|c} \text{real} & 0 \\ \hline \text{complex} & \text{real} \end{array}\right)$$

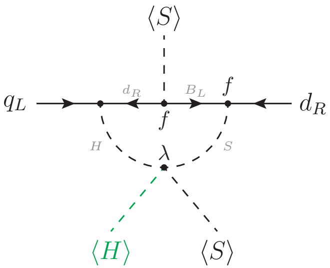
Barr criterion: $\det \left(\begin{array}{c|c} \text{real} & 0 \\ \hline \text{complex} & \text{real} \end{array}\right) = \text{real}$

So $\bar{\theta} = 0$ at tree-level

Coincidence $\mathscr{M}^{Bd} \sim \mathscr{M}^B$ necessary for CPV

Bento-Branco-Parada model

But it arises at 1-loop



Dine, Draper, JHEP'15

So $\boxed{\delta\bar{\theta} \sim \frac{f^2 \lambda_{HS}}{16\pi^2}}$

f transmit the SCPV to the SM

λ_{HS} Higgs portal

Model with non-conventional CP

Cherchiglia, Nishi, JHEP 1903 (2019) 040

- We can improve on BBP by using a nonconventional CP

CP4 in 3HDM, Ivanov, Silva, PRD'16

- Two VQLs B_1, B_2 (more fields), one scalar S
- $\delta\bar{\theta}$ vanishes at one-loop!
- No ad hoc $\mathbb{Z}_2$ is needed (embedded)
- 2-loop estimate:

$$\boxed{\delta\bar{\theta} \sim \frac{f^4 \lambda}{(16\pi^2)^2}}$$

Less suppression on the Yukawa f needed

Vector-like quarks of Nelson-Barr type

Cherchiglia, Nishi, JHEP'20

- If we find VLQs, how do we know it is related to the origin of CPV?
- The scalars that break CP needs to be much heavier to suppress mixing with H and then suppress 1-loop $\bar{\theta}$
- Only vector-like quarks (VLQs) at the TeV scale
- Consequences?

Vector-like quarks of Nelson-Barr type

VLQs of Nelson-Barr type (NB-VLQs) arise as

$$-\mathcal{L} = \bar{q}_{iL}\mathscr{Y}^{d}_{ij} H d_{jR} + \bar{q}_{iL}\mathscr{Y}^{u}_{ij}\tilde{H} u_{jR}$$
$$+ \ \bar{B}_{rL}\mathscr{M}^{Bd}_{rj} d_{jR} + \bar{B}_{rL}\mathscr{M}^{B}_{rs} B_{sR} + h.c.,$$

Down-type singlet NB-VLQ

Only $\mathscr{M}^{Bd}$ is complex $\implies$ soft breaking of CP

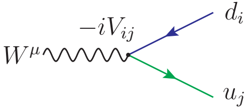
From parameter counting, one less parameters is needed compared to the generic VLQ.

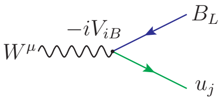
For $n_B = 1$:

	# of param.	# of CP-odd
SM	$3+3+3+1=10$	1
generic VLQ	16	3
NB-VLQ	15	1

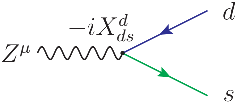
Generic Vector-like quarks

- Only 7 irreps with renormalizable mixing with SM quarks (only 3 are copies)
- We consider B_L, B_R copies of b_R
- The VLQs mix with the SM quarks: (d_L, s_L, b_L, B_L)
- The CKM matrix is no longer unitary but $\theta_{\text{mix}} \sim m_{\text{SM}}/M_{\text{VLQ}}$





- Flavor changing neutral currents (FCNC) are generically induced



Constraints on generic flavor structure

$\Delta F = 2$ observables

Operator	Bounds on Λ in TeV ($c_{\rm NP}=1$) Re	Im	Bounds on $c_{\rm NP}$ ($\Lambda = 1$ TeV) Re	Im	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ϵ_K
$(\bar{s}_R\, d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ϵ_K
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{c}_R\, u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p\rvert, \phi_D$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_R\, d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	Δm_{B_d}; $S_{\psi K_S}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	Δm_{B_s}; $S_{\psi\phi}$
$(\bar{b}_R\, s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	Δm_{B_s}; $S_{\psi\phi}$

Isidori, 1302.0661

Silvestrini, Valli, PLB'19, 1812.10913

For a generic flavor structure, new physics is restricted to lie $\Lambda_{NP} \gtrsim 100\,\mathrm{TeV}$.

With CPV ($K^0 - \bar{K}^0$), $\Lambda_{NP} \gtrsim 10^5\,\mathrm{TeV}$.

To be compatible with $\Delta F = 2$ observables with $\Lambda_{NP} \sim 1\,\mathrm{TeV}$,

$$|c_{ij}| \lesssim |V_{3i}^* V_{3j}|^2 \,.$$

BSM physics at 1TeV needs nongeneric flavor structure

VLQ of Nelson-Barr type

For down type NB-VLQ, mass matrix of size $3 + n_B$

$$\text{Real basis:} \qquad \mathscr{M}^{d+B} = \left(\begin{array}{c|c} v\mathscr{Y}^d/\sqrt{2} & 0 \\ \hline \mathscr{M}^{Bd} & \mathscr{M}^B \end{array}\right)$$

$$\text{Generic basis:} \qquad M^{d+B} = \left(\begin{array}{c|c} vY^d/\sqrt{2} & vY^B/\sqrt{2} \\ \hline 0 & M^B \end{array}\right)$$

by unitary transformation on righthanded fields (d_{iR}, B_R)

For $n_B = 1$

One Generic VLQ : 16 parameters

v.s.

One NB-VLQ : 15 parameters

VLQ of Nelson-Barr type

In leading seesaw $Y^d Y^{d\dagger}$ should attain SM values

$$V_{\text{CKM}} \ \mathrm{diag}(y_d^2, y_s^2, y_b^2) V_{\text{CKM}}^\dagger$$

So the CP phase in the CKM should come from the complex part in

$$\boxed{Y^d Y^{d\dagger} = \mathscr{Y}^d \left(\mathbb{1}_3 - ww^\dagger\right) \mathscr{Y}^{d\mathsf{T}}}$$

$$w = \mathscr{M}^{Bd\dagger} M^{B\dagger -1} \gtrsim 0.9$$

NB-VLQs cannot decouple

Correlations $\implies$ implications to flavor strucuture

Cherchiglia, Nishi, JHEP'20

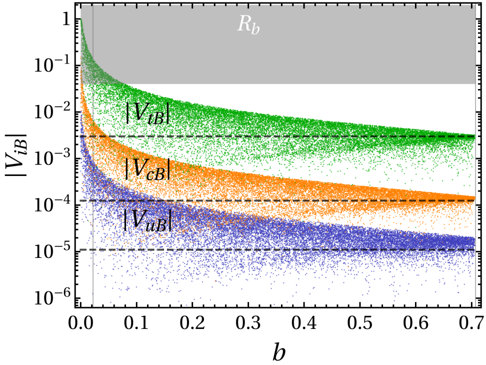
For $n_B = 1$, we can solve explicitly for

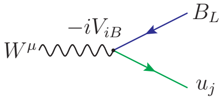
$$\boxed{\mathscr{Y}^d = \mathrm{Re}^{1/2}(Y^d Y^{d\dagger})\mathcal{O}..}$$

SM quark hierarchy

VLQ of Nelson-Barr type

$V_{iB} \approx \frac{v}{\sqrt{2}M_B} Y_i^B$ are hierarchical $\qquad M_B = 1.4\,\mathrm{TeV}$





- - - $0.003 \times (|V_{ib}|)$
$\sim 0.003 \times (0.004, 0.04, 1)$

Cherchiglia, Nishi, JHEP'20

$R_b = \Gamma(Z \to bb)/\Gamma(Z \to \text{hadrons})$

Largely flavor safe

VLQ of Nelson-Barr type: flavor constraints

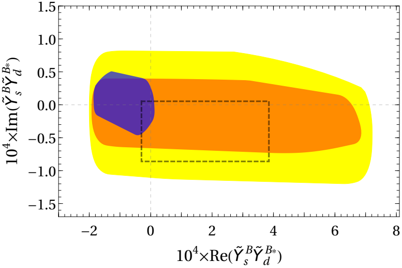
Finer details require a global fit. We consider

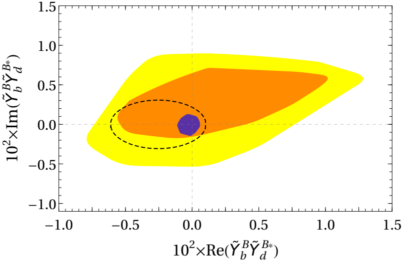
- $|V_{ij}|$, Δm_{B_d}, Δm_{B_s}
- $B_s \to \mu\bar{\mu}$, ϵ_K, $S_{\psi K_S}$
- R_b, ϵ'/ϵ, $K_L \to \mu\bar{\mu}$

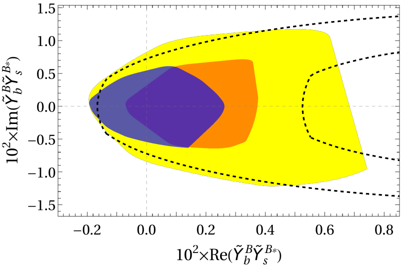
Cherchiglia, De Conto, Nishi, 2103.04798

VLQ of Nelson-Barr type: flavor constraints

Cherchiglia, De Conto, Nishi, 2103.04798 $\qquad M_B = 1.4\,\mathrm{TeV}$







- - - Bobeth, et al., JHEP 04 (2017), 079.

$$V_{iB} \approx \frac{v}{\sqrt{2}M_B}(V_{\mathrm{ckm}}\,\tilde{Y}^B)_i$$

NB-VLQ falsifiable!

Conclusions

- CP may be a symmetry of nature after all (spontaneously broken)
- Nelson-Barr mechanism may solve the strong CP problem and requires VLQs to transmit the CPV to the SM
- Even the simplest NB implementation has consequences to flavor
- NB-VLQs need one less parameter
- For one NB-VLQ, only one CP odd quantity and the model is largely flavor safe because V_{iB} are hierarchical

More details

- A. L. Cherchiglia, G. De Conto and C. C. Nishi, "Flavor constraints for a Vector-like quark of Nelson-Barr type," 2103.04798 [hep-ph].
- A. L. Cherchiglia and C. C. Nishi, "Consequences of vector-like quarks of Nelson-Barr type," JHEP **2008** (2020) 104 [2004.11318 [hep-ph]].
- A. L. Cherchiglia and C. C. Nishi, "Solving the strong CP problem with non-conventional CP," JHEP **1903** (2019) 040 [1901.02024 [hep-ph]].

Thank you!

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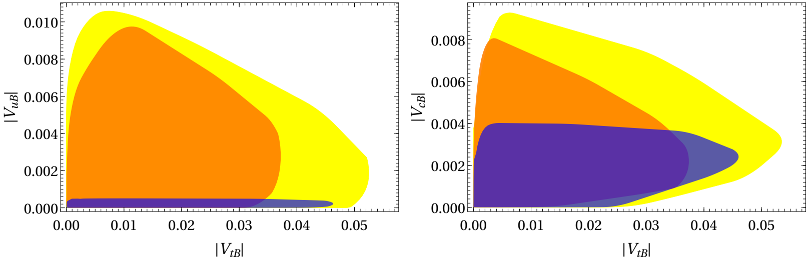
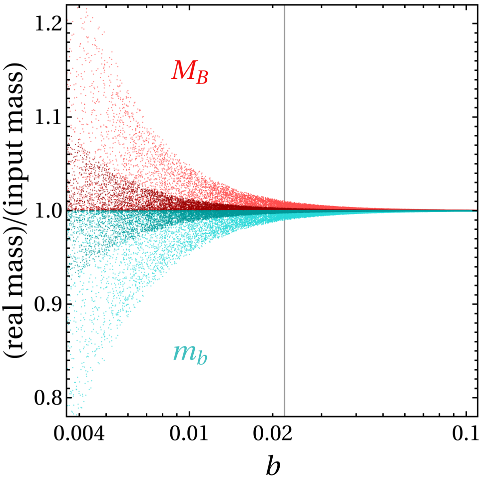
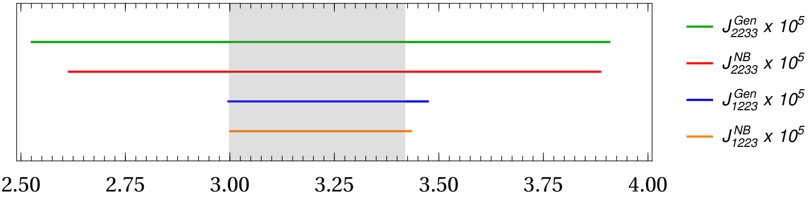
VLQ of Nelson-Barr type: flavor constraints



VLQ of Nelson-Barr type



VLQ of Nelson-Barr type



$$J_{ijkl} = \mathrm{Im}[V_{ij} V^\dagger_{jk} V_{kl} V^\dagger_{li}]$$

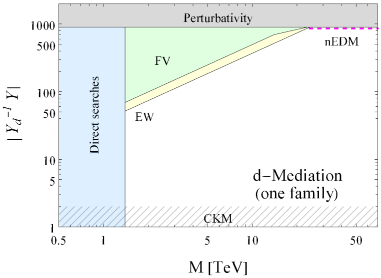
Irreducible contriutions to $\bar{\theta}$

There are *irreducible* contributions to $\bar{\theta}$ arising from the NB-VLQs.

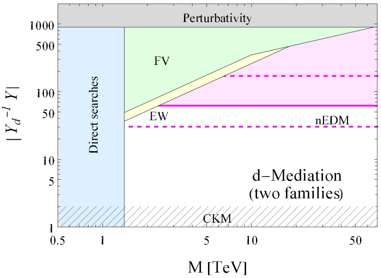
The non-decoupling contribution arises first at *3-loops*.

They are relevant for $n_B \geq 2$ and practically excludes $n_T \geq 2$.

Valenti, Vecchi, 2105.09122



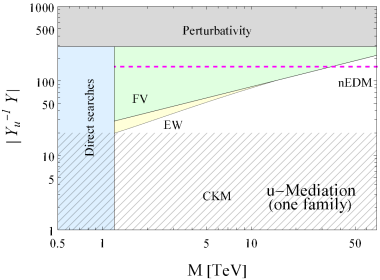
$n_B = 1$



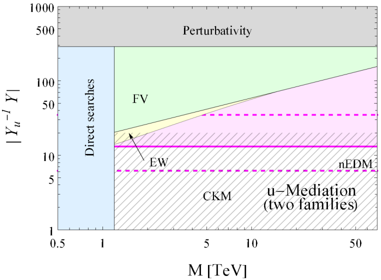
$n_B = 2$

Irreducible contriutions to $\bar{\theta}$

Valenti, Vecchi, 2105.09122



$n_T = 1$



$n_T = 2$