Leptonic CP violation from a vector-like lepton

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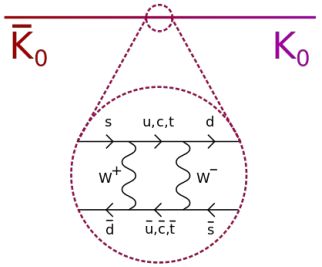
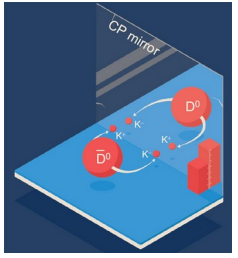
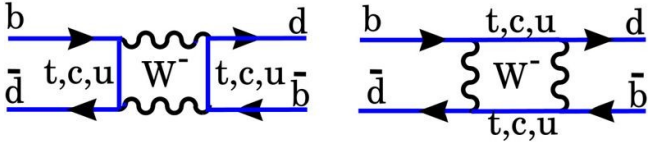
CP violation in quark systems



Cronin, Fitch - 1980



LHCb - 2019



Babar; Belle - 2001

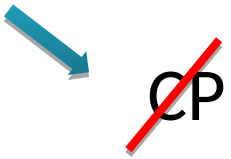
Nambu, Kobayashi, Maskawa - 2008

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

Weak force!

CP violation (strong)

$$\mathcal{L}_{QCD} = \bar{q}\left(i\not{D} - m_q e^{i\theta_q}\right) q - \frac{1}{4} G.G + \theta \frac{\alpha_s}{8\pi} G.\tilde{G}$$



Physical quantity: $\bar{\theta} = \theta - \theta_q$

Affects neutron eletric dipole moment $\bar{\theta} \leq 10^{-10}$

Baluni (1979), Crewther et al. (1979)

Why so small??

Strong CP problem

CP as a symmetry of the theory: spontaneously broken!

Nelson-Barr mechanism

Nelson (1984); Barr (1984)

Branco, Bento, Parada (1991)

SM + S + VLQ

$V_{\rm CKM}$ $\bar{\theta}_{tree} = 0$

Nelson-Barr VLQ

Cherchiglia, Nishi - JHEP 03 (2019) 040

Cherchiglia, Nishi - JHEP 08 (2020) 104

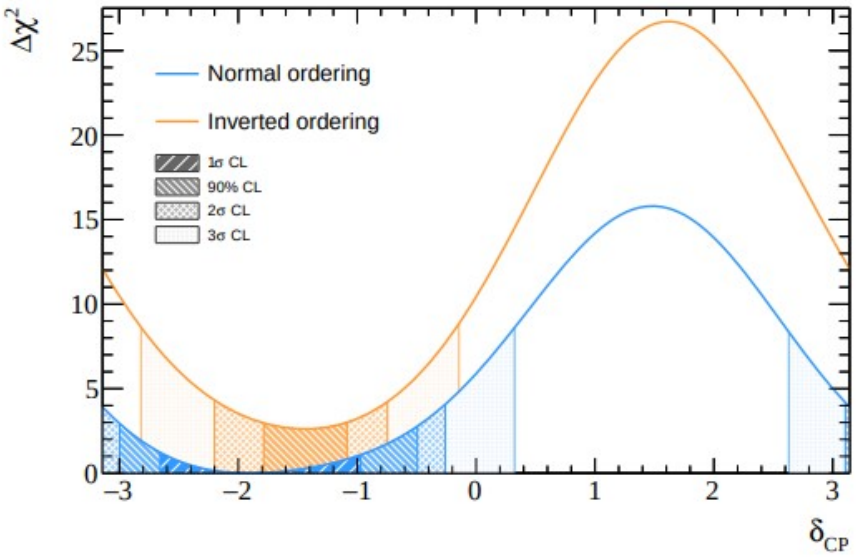
Cherchiglia, De Conto, Nishi - JHEP 11 (2021) 093

- Flavor consequences
- Comparison to generic VLQ models

$$-\mathcal{L} \supset \bar{q}_{iL}\mathcal{Y}^{d}_{ij}Hd_{jR} + \bar{B}_{rL}\mathcal{M}^{Bd}_{rj}d_{jR} + \bar{B}_{rL}\mathcal{M}^{B}_{rs}B_{sR} + h.c.,$$

Only source of CP violation in the model

What about leptons?



T2K collaboration: 2208.01164

Using **ONLY** T2K, CP-conserving hypothesis excluded at 90% C.L.

Similarly to quarks, ~~CP~~ is introduced in the mixing matrix (PMNS)

What if all CP violation is spontaneous in Nature?

Nelson-Barr VLL

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- Charged (singlet) VLL

Only source of CP violation in the model

$$-\mathcal{L} \supset \bar{l}_{iL}\mathcal{Y}^{e}_{ij}He_{jR} + \bar{E}_L\mathcal{M}^{Ee}_{j}e_{jR} + \bar{E}_L\mathcal{M}_E E_R + h.c.,$$

$$-\mathcal{L} \supset \bar{l}_{iL}Y^{e}_{ij}He_{jR} + \bar{l}_{iL}Y^{E}_{i}HE_R + \bar{E}_L M_E E_R + h.c.,$$

Nelson-Barr VLL

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$$-\mathcal{L} \supset \bar{l}_{iL}\mathcal{Y}^{e}_{ij}He_{jR} + \bar{E}_L\mathcal{M}^{Ee}_{j}e_{jR} + \bar{E}_L\mathcal{M}_E E_R + h.c.,$$

$$\frac{2}{v^2}V_{e_L}\,\mathrm{diag}(m_e^2, m_\mu^2, m_\tau^2)V_{e_L}^\dagger = \mathcal{Y}^e\left(\mathbb{1}_3 - \mathcal{M}^{Ee\,\dagger}M^{Ee}/M_E^2\right)\mathcal{Y}^{e\,\mathrm{T}}$$

$V_{e_L} \to V_{\mathrm{pmns}}^\dagger$

Nelson-Barr VLL

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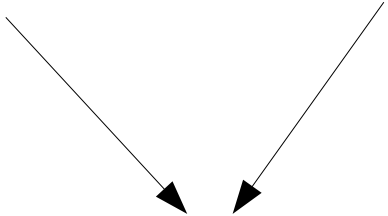
$$-\mathcal{L} \supset \bar{l}_{iL}\mathcal{Y}^{e}_{ij}He_{jR} + \bar{E}_L\mathcal{M}^{Ee}_{j}e_{jR} + \bar{E}_L\mathcal{M}_E E_R + h.c.,$$



Correlated!

$$\frac{2}{v^2}V_{e_L}\mathrm{diag}(m_e^2, m_\mu^2, m_\tau^2)V_{e_L}^\dagger = Y^e Y^{e\dagger}$$

$$-\mathcal{L} \supset \bar{l}_{iL}Y^{e}_{ij}He_{jR} + \bar{l}_{iL}Y^{E}_{i}HE_R + \bar{E}_L M_E E_R + h.c.,$$

Nelson-Barr VLL

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$$-\mathcal{L} \supset \bar{l}_{iL}\mathcal{Y}^{e}_{ij}He_{jR} + \bar{E}_L\mathcal{M}^{Ee}_{j}e_{jR} + \bar{E}_L\mathcal{M}_E E_R + h.c.,$$

Correlated!

$$Y^E = \mathcal{Y}^e\mathcal{M}^{Ee\dagger}/M_E$$

$$-\mathcal{L} \supset \bar{l}_{iL}Y^{e}_{ij}He_{jR} + \bar{l}_{iL}Y^{E}_{i}HE_R + \bar{E}_L M_E E_R + h.c.,$$

Nelson-Barr VLL

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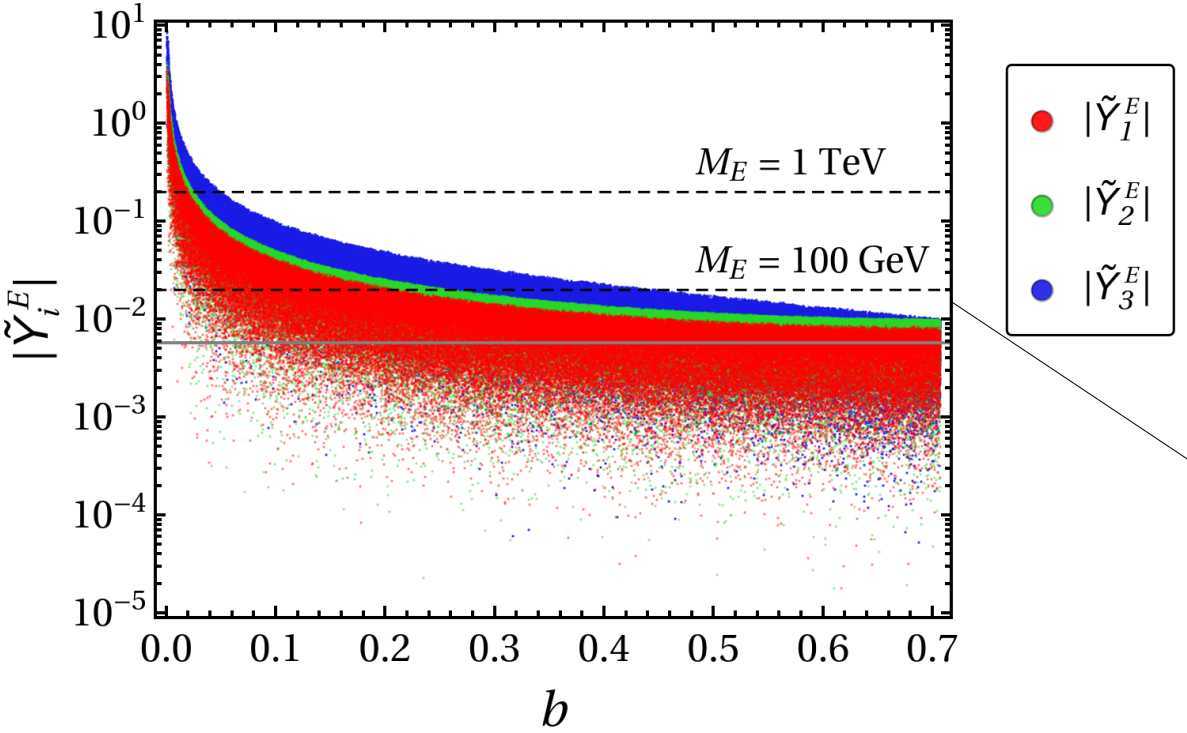

$$Y^E = \mathcal{Y}^e \mathcal{M}^{Ee\dagger}/M_E$$

$$\tilde{Y}^E = V_{\rm pmns} Y^E$$

EW precision fits
2008.01113

Nelson-Barr VLL

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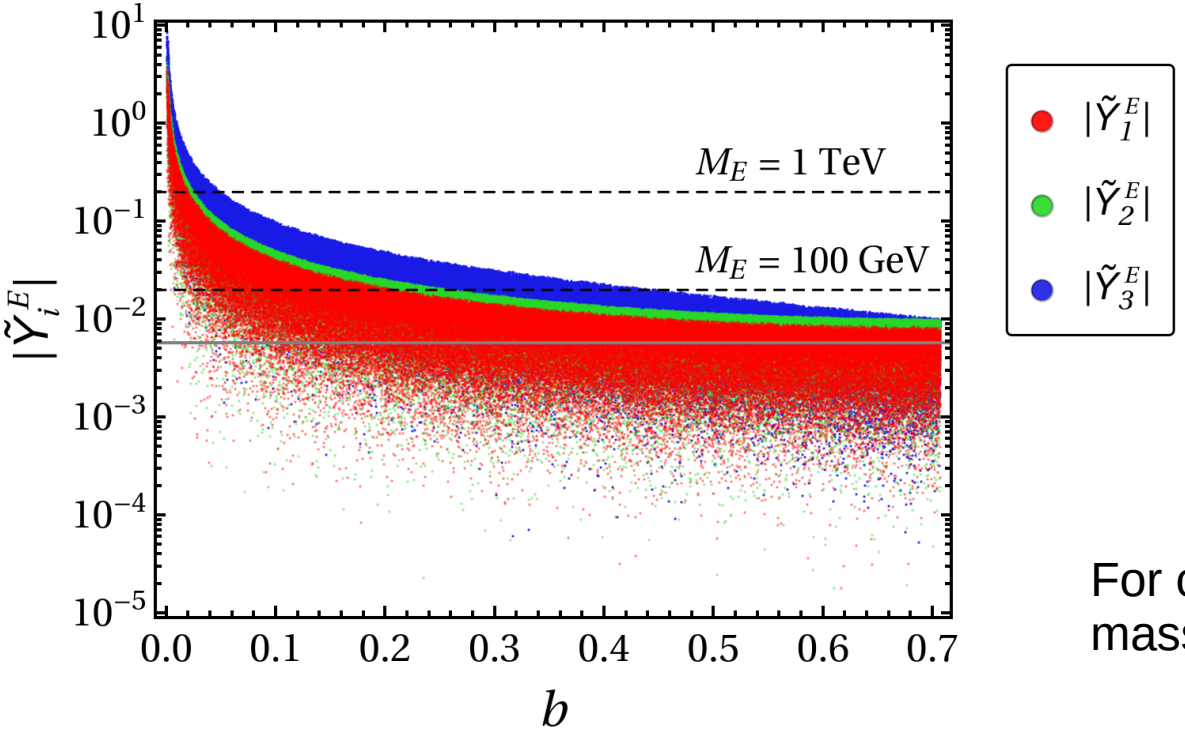

$\mu \to e$ conversion in gold

$$|\tilde{Y}_\mu^E \tilde{Y}_e^{E*}| < 5.0 \times 10^{-8} \left(\frac{M_E}{100\,GeV}\right)^2$$

For couplings of the same order, the VLL mass is bounded from below to 2.6 TeV

Nelson-Barr VLL

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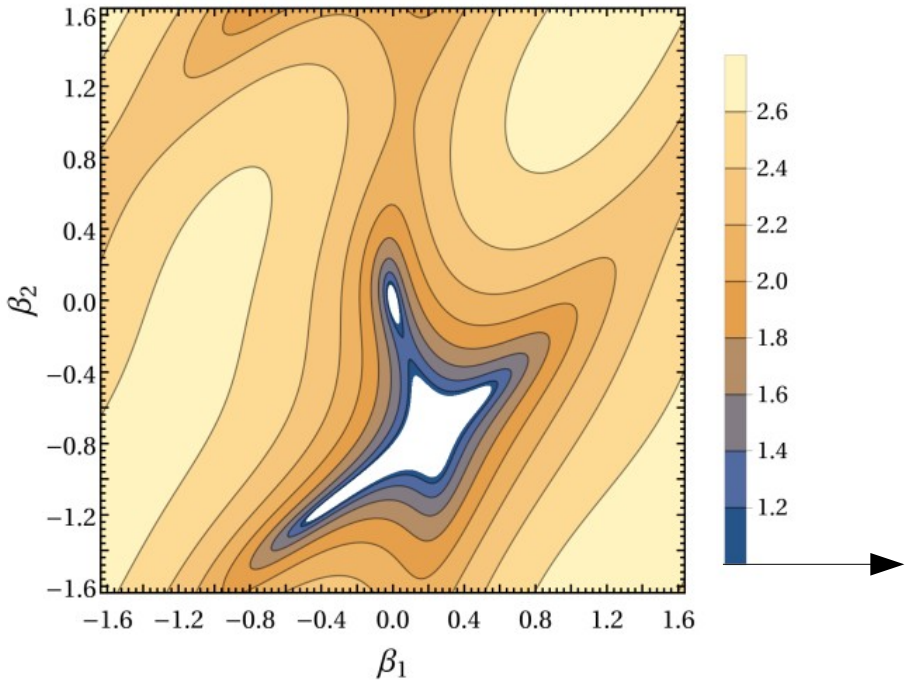

There are special points in parameter space that allow lower values though

$$\mathrm{V}_{pmns} = U(\theta_{12}, \theta_{23}, \theta_{13}, \delta) \begin{pmatrix} 1 & & \\ & e^{i\beta_1} & \\ & & e^{i(\delta+\beta_2)} \end{pmatrix}$$

$450GeV$

$$10^k \equiv 10^{+7} |\tilde{Y}_\mu^E \tilde{Y}_e^{E*}| < \left(\frac{M_E}{142\,GeV} \right)^2$$

Conclusions

- CP violation was observed in weak processes with quarks. A similar framework may occur with leptons;
- CP violation in the strong sector was not observed (strong CP problem), may CP be a spontaneously broken symmetry?
- We investigated a model inspired in the Nelson-Barr mechanism with focus only in vector-like leptons;
- Stringent limits apply due to CLFV (charged lepton flavour violation).
- However, special points exists. May be protected by some symmetry?