What does a non-vanishing neutrino mass have to say about the strong CP problem?

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DPF 2017, Fermilab, July 31- August 4, 2017

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- A new solution with testable experimental implications at the LHC (and beyond): smallness of neutrino masses $\Rightarrow$ smallness of the CP-violating parameter $\bar{\theta}$, below the experimental bound $\bar{\theta} < 10^{-10}$.
- Model: A model of fertile right-handed neutrinos at the electroweak scale (EW-ν_R model) involving mirror fermions. All the ingredients for a strong CP solution already contained in the EW-ν_R model. Mixing between mirror quarks and SM quarks via a Higgs singlet $\Rightarrow$ contribution to $\bar{\theta}$ proportional to the neutrino masses $\Rightarrow$ naturally small! Experimental implications in the search for mirror quarks!

The Strong CP problem

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- This contributes to the Electric Dipole Moment of the neutron: $d_n \approx 2.5\times10^{-16}\bar{\theta}e-cm$. Experimentally: $|d_n| < 2.9\times10^{-26}e-cm$!

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  - Several axion-less scenarios were proposed.

What does a neutrino mass have to do with all that stuff? The EW-scale ν_R model

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  - Right-handed Majorana neutrino masses: $g_M\, \nu_R^T\, \sigma_2\, \nu_R \chi^0$. $\langle \chi^0 \rangle = v_M$ $\Rightarrow M_R = g_M\, v_M$ $(v_M \sim O(\Lambda_{EW}))$.

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  - Seesaw: $m_\nu \sim m_D^2 / M_R$; M_R.

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- Yukawa interactions with quarks:

$$\mathcal{L}_{mass} = g_u \bar{q}_L \tilde{\Phi}_2 u_R + g_d \bar{q}_L \Phi_2 d_R + g_{u^M} \bar{q}^M{}_R \tilde{\Phi}_{2M} u_L^M + g_{d^M} \bar{q}^M{}_R \Phi_{2M} d_L^M + H.c.$$

$$\mathcal{L}_{mixing} = g_{Sq} \bar{q}_L \phi_S q^M{}_R + g_{Su} \bar{u}_L^M \phi_S u_R + g_{Sd} \bar{d}_L^M \phi_S d_R + H.c.$$

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- Extra global symmetries: $U(1)_{SM} \times U(1)_{MF}$ (to prevent some unwanted couplings for consistency). These contain the chiral symmetries: $U(1)_{A,SM} \times U(1)_{A,MF} \Rightarrow \mathcal{L}_{mixing}$ is invariant under: $q \to \exp(\imath \alpha_{SM} \gamma_5) q$; $q^M \to \exp(\imath \alpha_{MF} \gamma_5) q^M$; $\phi_S \to \exp(-\imath(\alpha_{SM} + \alpha_{MF}))\phi_S$.

Neutrino mass and Strong CP

- Chiral rotations: $\theta_{QCD} \rightarrow \theta_{QCD} - (\alpha_{SM} + \alpha_{MF})$. Can be rotated to zero! Next, compute $ArgDetM$ (actually $\theta_{Weak} = ArgDet(\mathcal{M}_u \mathcal{M}_d)$)

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- Mass matrices: $\mathcal{M}_u = \begin{pmatrix} m_u & |g_{Sq}| v_S \exp(\imath\theta_q) \\ |g_{Su}| v_S \exp(\imath\theta_u) & M_u \end{pmatrix}$,

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- Straightforward calculations give:

$$\bar{\theta} = \theta_{Weak} \approx \frac{-(r_u \sin(\theta_q+\theta_u) + r_d \sin(\theta_q+\theta_d))}{1 - r_u \cos(\theta_q+\theta_u) - r_d \sin(\theta_q+\theta_d)}$$

$$r_u = \frac{|g_{Sq}||g_{Su}| v_S^2}{m_u M_u} = \left(\frac{|g_{Sq}||g_{Su}|}{g_{Sl}^2}\right)\left(\frac{m_D^2}{m_u M_u}\right)$$

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- Putting in some reasonable numbers

$$\theta_{Weak} < -10^{-8}\{(\frac{|g_{Sq}||g_{Su}|}{g_{Sl}^2})\sin(\theta_q + \theta_u) + (\frac{|g_{Sq}||g_{Sd}|}{g_{Sl}^2})\sin(\theta_q + \theta_d)\}$$

Neutrino mass and Strong CP: Experimental implications

- The EW-scale ν_R model: (a) satisfies the EW-precision data, e.g. positive contributions to S from mirror fermions get cancelled by negative contributions from triplet scalars; (b) Two very distinct scenarios (Dr Jekyll and Mr Hyde) that can accommodate, in terms of signal strengths, the 125-GeV scalar; (c) Constraints from $\mu \rightarrow e\gamma$ and $\mu 2e$ conversion imply $g_{Sl} < 10^{-4}$ $\Rightarrow$ Decays of mirror leptons at DISPLACED VERTICES!

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- Other implications are under investigation.

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Conclusions

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- There seems to be a collusion between neutrino physics and QCD to make Strong CP great again! Stay tune!

Some papers

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- Searches: S. Chakdar, K. Ghosh, V. Hoang, P. Q. Hung and S. Nandi, Phys. Rev. D **93**, no. 3, 035007 (2016) doi:10.1103/PhysRevD.93.035007 [arXiv:1508.07318 [hep-ph]], S. Chakdar, K. Ghosh, V. Hoang, P. Q. Hung and S. Nandi, Phys. Rev. D **95**, no. 1, 015014 (2017) doi:10.1103/PhysRevD.95.015014

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- Need to restore the Custodial Symmetry! Another triplet Higgs scalar $\xi = (3, Y/2 = 0)$ such that

$$\chi = \begin{pmatrix} \chi^0 & \xi^+ & \chi^{++} \\ \chi^- & \xi^0 & \chi^+ \\ \chi^{--} & \xi^- & \chi^{0*} \end{pmatrix}$$

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- Lots of Higgses! Questions which are BSM $\Rightarrow$ More scalars!
- What about the Dirac mass m_D? It will come from a product of 2 doublets i.e. $m_D(\nu_L^\dagger \nu_R + h.c.)$. What Higgs?

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- Note: The magnitude of the magnetic moment for the electron or muon is $\mu = (1+a)\frac{q}{2m}$ where $a = \frac{g-2}{2}$. $a^{(4)} \sim \frac{1}{45}(\frac{m}{m_{heavy}})^2(\frac{\alpha}{\pi})^2$. For $m_{heavy} \sim 200\, GeV$, $a_e^{(4)} \sim 10^{-18}$ and $a_\mu^{(4)} \sim 10^{-14}$.

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- Under the custodial symmetry group $SU(2)_D$, these 10 physical degrees of freedom decompose as

$$\begin{aligned} \text{five-plet (quintet)} &\rightarrow H_5^{\pm\pm},\ H_5^{\pm},\ H_5^0; \\ \text{triplet} &\rightarrow H_3^{\pm},\ H_3^0; \\ \text{two singlets} &\rightarrow H_1^0,\ H_1^{0\prime} \end{aligned}$$

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- These scalars are expressed in terms of the original fields as

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H_5^{++} &= \chi^{++},\ H_5^{+} = \zeta^{+},\ H_3^{+} = c_H \psi^{+} - s_H \phi^{+}, \\
H_5^{0} &= \frac{1}{\sqrt{6}}\left(2\xi^0 - \sqrt{2}\chi^{0r}\right),\ H_3^0 = \imath\left(c_H \chi^{0\imath} + s_H \phi^{0\imath}\right), \\
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- $s_H = \frac{2\sqrt{2}\, v_M}{v}, \qquad c_H = \frac{v_2}{v}$

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- These scalars make important contributions to the electroweak precision parameters which offset those of the mirror fermions!