Strong CP and Neutrino Masses: A Common Origin of Two Small Scales

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Strong CP Problem Overview

The ninth goldstone boson which is missing in the low energy QCD ($U(1)_A$ problem) has been elegantly solved by ‘t Hooft who pointed out that the instanton effects at the quantum level will explicitly break the $U(1)_A$ [1]. The resulting η' mass will be the order of the QCD scale instead of pion-mass scale. Precisely due to the QCD solution to the $U(1)_A$ problem, the θ term in QCD becomes physically relevant. The relevance of the θ term can be studied at lattice and by using the current algebra. The most stringent bound $\theta < 10^{-10}$ comes from the neutron electric dipole moment [2], whose contribution from θ term has been calculated in [3, 4]. Such small numbers call for an explanation. Various solutions have been proposed including adding a dynamical axion field [5–7], making CP an exact symmetry [8, 9] and using massless up quark as a solution [10–13]. Note that one can re-interpret the bound on θ to the imaginary part of up quark mass by making a chiral transformation $u_R \to e^{i\theta} u_R$ and the bound would become $\mathcal{I}[m_u] < 4.0 \times 10^{-4}$ eV.
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Neutrino Masses

The discovery of neutrino oscillation indicates the non-zero values of neutrino masses [14, 15], which is a sign of new physics beyond SM. Although one can simply extend the SM by adding the right-handed neutrinos, it would be very nice that we can learn something new when explaining the smallness. One of the most attractive idea is the seesaw mechanism [16–18], which generates the tiny neutrino masses (~ 0.05 eV) from one large scale $M \sim 10^{15}$ GeV as $m_\nu \sim v^2/M$. The scale M can be associated with the Majorana fermion mass scale as in [19] or the scalar mass as in the Dirac seesaw models [20, 21], although the latter case needs to stabilize the scalar masses with respect to the Planck scale.

Dirac Seesaw and Neutron EDM

In [22], we have taken the closeness of the two scales $\mathcal{I}[m_u]$ and m_ν as an indication and explored the Dirac seesaw mechanism [20, 21] and its supersymmetric extension to provide a common origin. The real part of the up quark mass obtains additive renormalization from instanton effects above the chiral symmetry breaking scale ~ 1 GeV to be consistent with observed large low energy chiral up quark mass $\sim$ MeV. Example involves the ultraviolet extension of QCD to $SU(3)^3$ gauge groups with each generation of quarks charged under different group [23]. Small instanton associated with gauge groups can give contribution to the Yukawas of up, strange and bottom quarks to the SM Higgs, which are forbidden by some discrete

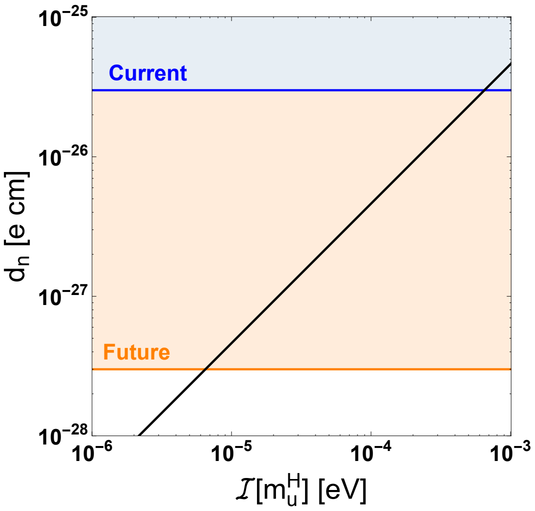

Figure 1: The neutron EDM as a function of the imaginary part of the up quark mass $\mathcal{I}[m_u] = \mathcal{I}[m_u^H]$. The blue and orange horizontal lines indicate the current 90% C.L. bound [2] and prospective sensitivity from the future neutron EDM measurements [24–30].

symmetries at tree-level. Irrespective of the detailed origin of this additive instanton contribution, the novel part of our construction is that the neutrino mass scale is strongly correlated with the static non-zero value of the neutron EDM as shown in Fig. 1, with predicted values that are expected to be probed by the next generation of experiments [24–30]. In the Snowmass 2021, we plan to study if it is possible to further predict quantitative relation between neutrino mass and the value of neutron EDM, because previous model can only give a similar scale between the two.

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