Parity Solution to the Strong CP Problem in Pati-Salam Models

K.S. Babu

Oklahoma State University

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Based on:

Universal Seesaw Pati-Salam Model with P for Strong CP,
K.S. Babu and Sumit Biswas, [arXiv:2512.25028 [hep-ph]].

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CP Invariance of Strong Interactions

- Strong interactions appear to conserve Parity (P) and Time Reversal (T) symmetries, and therefore also CP symmetry. However, QCD Lagrangian admits a source of P and T violation:

$$\mathcal{L}_{\rm QCD} = -\frac{1}{4} G_{\mu\nu} G^{\mu\nu} + \theta_{QCD} \frac{g_s^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu} + \overline{q} \left(i\gamma^\mu D_\mu - m_q e^{i\theta_q \gamma_5} \right) q$$

- A chiral rotation on the quark field, $q \to e^{i\alpha\gamma_5/2} q$, can remove the phase of the quark mass as $\theta_q \to \theta_q - \alpha$. Due to the anomalous nature of this rotation, θ_{QCD} also changes to $\theta_{QCD} \to \theta_{QCD} + \alpha$

- The parameter

$$\overline{\theta} = \theta_{QCD} + \theta_q$$

  is invariant, and is physical

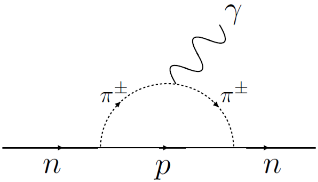
- With multiple flavors of quarks, the invariant physical parameter is

$$\overline{\theta} = \theta_{QCD} + \mathrm{ArgDet}(M_Q)$$

- $\overline{\theta}$ contributes to neutron Electric dipole moment (EDM)

Neutron EDM from $\overline{\theta}$

- In presence of $\overline{\theta}$ neutron will develop an electric dipole moment:



$$d_n \simeq \frac{e\,\overline{\theta}\,g_A\,c_+\,\mu}{8\pi^2 f_\pi^2}\mathrm{Log}\left(\frac{\Lambda^2}{m_\pi^2}\right) \simeq 3\times 10^{-16}\,\overline{\theta}\,\mathrm{e\ cm}$$

Here $\mu = \frac{m_u m_d}{m_u+m_d}$, $g_A \simeq 1.27$, $c_+ \simeq 1.6$, $\Lambda = 4\pi f_\pi$

- From $d_n < 1.8\times 10^{-26}$ e cm, one obtains $\Rightarrow \overline{\theta} < 10^{-10}$

- A lack of understanding of the extreme smallness of $\overline{\theta}$ is the strong CP problem

- Setting $\overline{\theta}$ to zero is unnatural, since weak interactions require $\mathcal{O}(1)$ CP violation in that sector

Parity Solution to the Strong P Problem

- Imagine Parity is spontaneously broken. $\Rightarrow$

$$\theta_{QCD} = 0 \text{ by Parity.}$$

- If the quark mass matrix is hermitian, also by Parity, then $\bar{\theta} = 0$ at tree-level.
- Quantum corrections could induce small nonzero $\bar{\theta}$.
- In left-right symmetric models, Parity symmetry is exact, with

$$q_L \leftrightarrow q_R, \qquad \Phi \leftrightarrow \Phi^\dagger$$

- Consequently, the Yukawa coupling $(Y_q\, \bar{q}_L\, \Phi\, q_R)$ is hermitian:

$$Y_q = Y_q^\dagger$$

- However, the quark mass matrix is

$$M_q = Y_q \langle \Phi \rangle$$

- It is a challenge to make the VEVs of Φ real.
- Initial attempts used discrete symmetries to achieve this goal. Mohapatra, Senjanovic (1978)

Left-Right Symmetry with Universal Seesaw

- Gauge symmetry is extended to $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_X$
- These models are motivated on several grounds:
  - Provide understanding of Parity violation
  - Better understanding of smallness of Yukawa couplings
  - Requires right-handed neutrinos to exist
  - Provide a solution to the strong CP problem via Parity
  - Naturally light *Dirac neutrinos* may be realized
  - Possible relevance to experimental anomalies

Davidson, Wali (1987) – universal seesaw
Babu, He (1989) – Dirac neutrino
Babu, Mohapatra (1990) – solution to strong CP problem via parity
Babu, Dutta, Mohapatra (2018) – R_{D^*} solution
Dunsky, Hall, Harigaya (2019) – spontaneous P breaking
Craig, Garcia Garcia, Koszegi, McCune (2020) – flavor constraints
Babu, He, Su, Thapa (2022) – neutrino oscillations with Dirac neutrinos
Harigaya, Wang (2022) – Baryogenesis
Babu, Dcruz (2022) – Cabibbo anomaly, W mass anomaly
Babu, Berbig, Goswami, Vastasyan (2025) – Leptogenesis

Left-Right Symmetry with Small $\overline{\theta}$

- Fermion transformation: $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$:

$$Q_L\ (3,2,1,1/3) = \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad Q_R\ (3,1,2,1/3) = \begin{pmatrix} u_R \\ d_R \end{pmatrix},$$

$$\Psi_L\ (1,2,1,-1) = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \Psi_R\ (1,1,2,-1) = \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}.$$

- Vector-like fermions are introduced to realize seesaw for charged fermion masses:

$$P(3,1,1,4/3), \quad N(3,1,1,-2/3), \quad E(1,1,1,-2)\ .$$

- Higgs sector is very simple:

$$\chi_L\ (1,2,1,1) = \begin{pmatrix} \chi_L^+ \\ \chi_L^0 \end{pmatrix}, \quad \chi_R\ (1,1,2,1) = \begin{pmatrix} \chi_R^+ \\ \chi_R^0 \end{pmatrix}$$

- $\langle \chi_R^0 \rangle = \kappa_R$ breaks $SU(2)_R \times U(1)_X$ down to $U(1)_Y$, and $\langle \chi_L^0 \rangle = \kappa_L$ breaks the electroweak symmetry with $\kappa_R \gg \kappa_L$

Seesaw for Charged Fermion Masses

- Yukawa interactions:

$$\mathcal{L} = y_u\ (\bar{Q}_L\tilde{\chi}_L + \bar{Q}_R\tilde{\chi}_R)P + y_d\ (\bar{Q}_L\chi_L + \bar{Q}_R\chi_R)N \\ + y_\ell\ (\bar{\Psi}_L\chi_L + \bar{\Psi}_R\chi_R)E + h.c.$$

- Vector-like fermion masses:

$$\mathcal{L}_{\rm mass} = M_{P^0}\ \bar{P}P + M_{N^0}\ \bar{N}N + M_{E^0}\ \bar{E}E$$

- Seesaw for charged fermion masses:

$$M_F = \begin{pmatrix} 0 & y\kappa_L \\ y^\dagger\kappa_R & M \end{pmatrix} \Rightarrow m_f = \frac{y^2\kappa_L\kappa_R}{M}$$

- Under Parity, fields transform as:

$$Q_L \leftrightarrow Q_R, \quad \Psi_L \leftrightarrow \Psi_R, \quad F_L \leftrightarrow F_R, \quad \chi_L \leftrightarrow \chi_R$$

  Consquently $y_{u,d,\ell} = y^\dagger_{u,d,\ell}$, and $M_{F^0} = M^\dagger_{F^0}$

- $\theta_{QCD} = 0$ due to Parity; ArgDet$(M_U M_D) = 0$; induced $\overline{\theta} = 0$ at one-loop; small and finite $\overline{\theta}$ arises at two-loop

Pati-Salam Models with **P** for Strong CP

- Pati-Salam models unify quarks with leptons with lepton number identified as the fourth color   Pati, Salam (1974)

- Gauge symmetry $SU(2)_L \times SU(2)_R \times SU(4)_c$ with quarks and leptons transforming as:

$$\Psi_L(2,1,4) = \begin{pmatrix} u_1 & u_2 & u_3 & \nu \\ d_1 & d_2 & d_3 & e \end{pmatrix}_L , \quad \Psi_R(1,2,4) = \begin{pmatrix} u_1 & u_2 & u_3 & \nu \\ d_1 & d_2 & d_3 & e \end{pmatrix}_R$$

- The Higgs sector in our model is very minimal:

$$H_L(2,1,4) = \begin{pmatrix} \chi_1^u & \chi_2^u & \chi_3^u & \chi^\nu \\ \chi_1^d & \chi_2^d & \chi_3^d & \chi^e \end{pmatrix}_L , \quad H_R(1,2,4) = \begin{pmatrix} \chi_1^u & \chi_2^u & \chi_3^u & \chi^\nu \\ \chi_1^d & \chi_2^d & \chi_3^d & \chi^e \end{pmatrix}_R$$

- Neutral components of the Higgs acquire VEVs:

$$\langle \chi_L^\nu \rangle = \kappa_L, \quad \langle \chi_R^\nu \rangle = \kappa_R \qquad (\kappa_R \gg \kappa_L)$$

- Symmetry breaking chain:

$$SU(2)_L \times SU(2)_R \times SU(4)_c \xrightarrow{\kappa_R} SU(2)_L \times U(1)_Y \times SU(3)_c \xrightarrow{\kappa_L} SU(3)_c \times U(1)_{\rm em}$$

- Fermion masses arise through mixing with vector-like fermions

Universal Seesaw Pati-Salam Models

- Vector-like fermions belonging to $\Sigma_L(1,1,15) + \Omega_{L,R}(1,1,10)$ with Standard Model decompositions

$$\begin{aligned} \Sigma_L(1,1,15) &= U(3,1,\frac{2}{3}) + U^c(\overline{3},1,-\frac{2}{3}) + \mathcal{O}(8,1,0) + N(1,1,0) \\ \Omega_{L,R}(1,1,10) &= D_{L,R}(3,1,-\frac{1}{3}) + E^-_{L,R}(1,1,-1) + \mathcal{S}_{L,R}(6,1,\frac{1}{3}) \end{aligned}$$

can generate realistic quark and lepton masses and mixings

- Note the presence of $U_{L,R},\ D_{L,R}, E_{L,R}$ as in the left-right model
- The new $N(1,1,0)$ fermion induces Majorana neutrino masses
- The color octet fermion $\mathcal{O}(8,1,0)$ and the color sextet fermion $\mathcal{S}(6,1,\frac{1}{3})$ are novel to Pati-Salam models
- Parity-symmetric Yukawa couplings are:

$$\begin{aligned} \mathcal{L}_{\rm Yuk} &= \sqrt{2} Y_{15}^\dagger \left\{ {\rm Tr}\left(\Sigma_L \Psi_L^T H_L^*\right) + {\rm Tr}\left(\overline{\Sigma}_L \Psi_R^T H_R^*\right) \right\} \\ &- \sqrt{2} Y_{10} \left\{ {\rm Tr}\left(\overline{\Psi}_L \tilde{H}_L \Omega_R\right) + {\rm Tr}\left(\overline{\Psi}_R \tilde{H}_R \Omega_L\right) \right\} \\ &+ M_{10}\, \overline{\Omega}_L \Omega_R + M_{15}\, (\overline{\Sigma^c})_R \Sigma_L + h.c. \end{aligned}$$

- One should establish that the quark and lepton masses are realistic within the setup, which is challenging due to quark-lepton symmetry

Realistic Fermion Masses

- Charged fermion mass matrices:

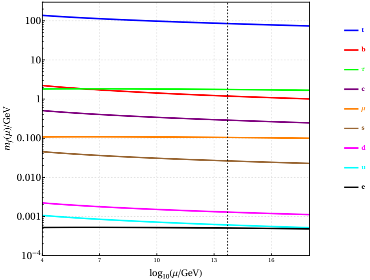
$$\mathcal{M}_u = \begin{pmatrix} 0 & Y_{15}\kappa_L \\ Y_{15}^\dagger \kappa_R & M_{15}^\dagger \end{pmatrix},\ \mathcal{M}_d = \begin{pmatrix} 0 & Y_{10}\kappa_L \\ Y_{10}^\dagger \kappa_R & M_{10} \end{pmatrix},\ \mathcal{M}_e = \begin{pmatrix} 0 & \sqrt{2}Y_{10}\kappa_L \\ \sqrt{2}Y_{10}^\dagger \kappa_R & M_{10} \end{pmatrix}$$

- Color octet and sextet masses: $\mathcal{M}_{\mathcal{O}} = M_{15}^\dagger, \quad \mathcal{M}_{\mathcal{S}} = M_{10}$
- Parity symmetry implies: $\mathcal{M}_{15}^\dagger = M_{15}, \quad \mathcal{M}_{10}^\dagger = M_{10}$
- Seesaw formula for light fermion masses with $(Y_{15}^\dagger \kappa_R M_{15}^{-1}) \ll 1$ and $(Y_{10}^\dagger \kappa_R M_{10}^{-1}) \ll 1$:

$$\begin{aligned} M_u &\simeq -\left(Y_{15} M_{15}^{-1} Y_{15}^\dagger\right) \kappa_L \kappa_R, \\ M_d &\simeq -\left(Y_{10} M_{10}^{-1} Y_{10}^\dagger\right) \kappa_L \kappa_R, \\ M_e &\simeq -2\left(Y_{10} M_{10}^{-1} Y_{10}^\dagger\right) \kappa_L \kappa_R \end{aligned}$$

- The relation $M_e = 2M_d$ is inconsistent, when compared to masses at the parity restoration scale of $\mu_P \simeq 5 \times 10^{13}$ GeV
- Parity restoration scale $\mu_P \simeq 5 \times 10^{13}$ GeV is the scale where $g_{2L} = g_{2R}$
- Including radiative corrections, we find the masses can be realistic

Running Fermion Masses

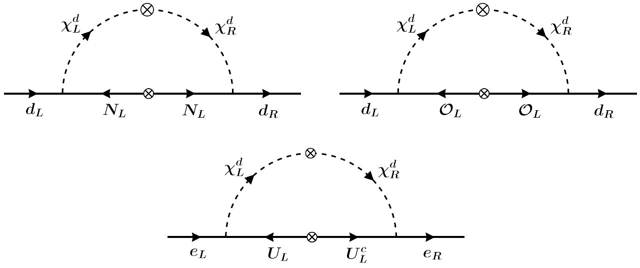


$m_f(\mu_P)$	[GeV]
m_t	8.50×10^{1}
m_b	1.19
m_τ	1.76
m_c	2.89×10^{-1}
m_μ	1.04×10^{-1}
m_s	2.63×10^{-2}
m_d	1.29×10^{-3}
m_u	6.06×10^{-4}
m_e	5.05×10^{-4}

Fermion masses at the Parity restoration scale $\mu_P \simeq 5 \times 10^{13}$ GeV

Radiative Corrections to M_d and M_e

- One-loop diagrams mediated by leptoquark scalars proportional to third family Yukawa couplings can correct M_d and M_e



$$\Delta M_d \simeq \left(\frac{11}{4}\right) \frac{Y_{15} M_{15} Y_{15}^\dagger}{16\pi^2} (2\lambda_5 \kappa_L \kappa_R) F(M_{15_3}^2, M_{\chi_1^d}^2, M_{\chi_2^d}^2)$$

$$\Delta M_e \simeq (3) \frac{Y_{15} M_{15} Y_{15}^\dagger}{16\pi^2} (2\lambda_5 \kappa_L \kappa_R)\ F(M_{15_3}^2, M_{\chi_1^d}^2, M_{\chi_2^d}^2)$$

$$F(x, y, z) = \frac{x \log x}{(x-y)(x-z)} + \frac{y \log y}{(y-x)(y-z)} + \frac{z \log z}{(z-x)(z-y)}$$

Benchmark Fit

- With loop corrections M_d and M_e are not proportional:

$$M_d = \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{12}^* & m_{22} & m_{23} \\ m_{13}^* & m_{23}^* & m_{33} \end{pmatrix} + \frac{11}{5} m_0 \begin{pmatrix} |\delta_1|^2 & \delta_1\delta_2^* & \delta_1\delta_3^* \\ \delta_1^*\delta_2 & |\delta_2|^2 & \delta_2\delta_3^* \\ \delta_1^*\delta_3 & \delta_2^*\delta_3 & |\delta_3|^2 \end{pmatrix},$$

$$M_e = 2 \begin{pmatrix} m_{11} & m_{12} & m_{13} \\ m_{12}^* & m_{22} & m_{23} \\ m_{13}^* & m_{23}^* & m_{33} \end{pmatrix} + \frac{12}{5} m_0 \begin{pmatrix} |\delta_1|^2 & \delta_1\delta_2^* & \delta_1\delta_3^* \\ \delta_1^*\delta_2 & |\delta_2|^2 & \delta_2\delta_3^* \\ \delta_1^*\delta_3 & \delta_2^*\delta_3 & |\delta_3|^2 \end{pmatrix}$$

- Here we defined

$$\begin{aligned} \delta_i &= (Y_{15})_{i3}, \\ m_0 &= \left(\frac{5}{4}\right) \frac{(M_{15})_3}{16\pi^2} (2\lambda_5 \kappa_L \kappa_R)\, F(M_{15_3}^2, M_{\chi_1^d}^2, M_{\chi_2^d}^2) \end{aligned}$$

- A good fit to down quark and charged lepton masses can be obtained by choosing M_e to be diagonal:

$$M_e = \begin{pmatrix} m_e & & \\ & m_\mu & \\ & & m_\tau \end{pmatrix}, \quad M_d = \begin{pmatrix} \frac{m_e}{2} + m_0|\delta_1|^2 & m_0\delta_1\delta_2^* & m_0\delta_1\delta_3^* \\ m_0\delta_1^*\delta_2 & \frac{m_\mu}{2} + m_0|\delta_2|^2 & m_0\delta_2\delta_3^* \\ m_0\delta_1^*\delta_3 & m_0\delta_2^*\delta_3 & \frac{m_\tau}{2} + m_0|\delta_3|^2 \end{pmatrix}$$

Sample Fit

- Mass eigenvalues are found as:

$$
\begin{aligned}
m_b &\simeq \frac{m_\tau}{2} + |\delta_3|^2 m_0 \\
m_s m_b &\simeq \frac{m_\mu m_\tau}{4} + \frac{1}{2}|\delta_2|^2 m_0 m_\tau + \frac{1}{2}|\delta_3|^2 m_0 m_\mu \\
m_d m_s m_b &\simeq \frac{m_e m_\mu m_\tau}{8} + \frac{1}{4}|\delta_3|^2 m_0 m_e m_\mu + \frac{1}{4}|\delta_2|^2 m_0 m_e m_\tau + \frac{1}{4}|\delta_1|^2 m_0 m_\mu m_\tau
\end{aligned}
$$

- From the fermion masses at μ_P, we obtain

$$
|\delta_3|^2 m_0 = 0.313 \text{ GeV}, \quad |\delta_2|^2 m_0 = 0.035 \text{ GeV}, \quad |\delta_1|^2 m_0 = 7.09 \times 10^{-4} \text{ GeV}
$$

- A sample choice of model parameters:

$$
M^d_{\chi_1} = M^d_{\chi_2} = \kappa_R, (M_{15})_3 = 4\kappa_R, (Y_{15})_{33} = 1.434, (Y_{15})_{23} = 0.481, (Y_{15})_{13} = 0.068
$$

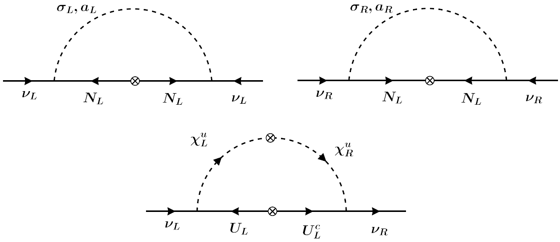
- This shows the consistency of the model

Radiative Neutrino Masses

- Neutrino masses are zero at tree-level. $\mathcal{M}_\nu$ spanning (ν, ν^c, N) is

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & 0 & -\frac{\sqrt{3}}{2} Y_{15}^* \kappa_L \\ 0 & 0 & -\frac{\sqrt{3}}{2} Y_{15} \kappa_R \\ -\frac{\sqrt{3}}{2} Y_{15}^\dagger \kappa_L & -\frac{\sqrt{3}}{2} Y_{15}^T \kappa_R & M_{15} \end{pmatrix}$$

- Loop diagrams correct the upper 2×2 block



- Loop-corrected mass matrix:

$$\mathcal{M}_\nu = \begin{pmatrix} m_L & m_\nu^D & -\frac{\sqrt{3}}{2} Y_{15}^* \kappa_L \\ (m_\nu^D)^T & m_R & -\frac{\sqrt{3}}{2} Y_{15} \kappa_R \\ -\frac{\sqrt{3}}{2} Y_{15}^\dagger \kappa_L & -\frac{\sqrt{3}}{2} Y_{15}^T \kappa_R & M_{15} \end{pmatrix}$$

- Similar to radiative correction to seesaw in SM

Sierra, Yaguna (2011); Dev, Pilaftsis (2012)

Radiative Neutrino Masses

- Light 3×3 neutrino mass matrix:

$$M_\nu^\ell \approx m_L - \begin{pmatrix} m_\nu^D & -\frac{\sqrt{3}}{2} Y_{15}^* \kappa_L \end{pmatrix} \begin{pmatrix} m_R & -\frac{\sqrt{3}}{2} Y_{15} \kappa_R \\ -\frac{\sqrt{3}}{2} Y_{15}^T \kappa_R & M_{15} \end{pmatrix}^{-1} \begin{pmatrix} (m_\nu^D)^T \\ -\frac{\sqrt{3}}{2} Y_{15}^\dagger \kappa_L \end{pmatrix} .$$

$$\approx -\frac{\kappa_L}{\kappa_R} \left(m_\nu^D \, (Y_{15}^T)^{-1} Y_{15}^\dagger + Y_{15}^* \, Y_{15}^{-1} (m_\nu^D)^T \right) + \frac{\kappa_L^2}{\kappa_R^2} \left(Y_{15}^* \, Y_{15}^{-1} \, m_R \, (Y_{15}^T)^{-1} Y_{15}^\dagger \right) + m_L$$

- Light and heavy Majorana mass matrices via loops:

$$m_L \simeq \frac{3}{4} Y_{15}^\dagger M_{15} \left[\frac{3}{32\pi^2} \frac{M_{Z_L}^2}{M_{15_3}^2 - M_{Z_L}^2} \ln\left(\frac{M_{15_3}^2}{M_{Z_L}^2} \right) + \frac{1}{32\pi^2} \frac{M_{\sigma_L}^2}{M_{15_3}^2 - M_{\sigma_L}^2} \ln\left(\frac{M_{15_3}^2}{M_{\sigma_L}^2} \right) \right] Y_{15}^*$$

$$m_R \simeq \frac{3}{4} Y_{15}^\dagger M_{15} \left[\frac{3}{32\pi^2} \frac{M_{Z_R}^2}{M_{15_3}^2 - M_{Z_R}^2} \ln\left(\frac{M_{15_3}^2}{M_{Z_R}^2} \right) + \frac{1}{32\pi^2} \frac{M_{\sigma_R}^2}{M_{15_3}^2 - M_{\sigma_R}^2} \ln\left(\frac{M_{15_3}^2}{M_{\sigma_R}^2} \right) \right] Y_{15}^*$$

- This leads to realistic neutrino masses and mixing angles: For e.g.,

$$\text{Input :} \qquad (\lambda_3 + \lambda_4) = 1.5, \qquad Y_{15} = 1,$$

$$M_{15_3} = 5 \times 10^{13} \text{ GeV}, \qquad M_{\sigma_L} = 125 \text{ GeV}, \qquad M_{\sigma_R} = 7 \times 10^{13} \text{ GeV},$$

$$\text{Output :} \qquad m_\nu \approx 0.05 \, \text{eV}$$

$\overline{\theta}$ at one-loop

- Correction to the quark mass matrix:

$$\mathcal{M}_U = \mathcal{M}_U^0 (1 + C)$$

- $\overline{\theta}$ is given by

$$\overline{\theta} = \mathrm{ArgDet}(1 + C) = \mathrm{ImTrln}(1 + C) = \mathrm{ImTr}\, C_1$$

where a loop-expansion is used:

$$C = C_1 + C_2 + \ldots$$

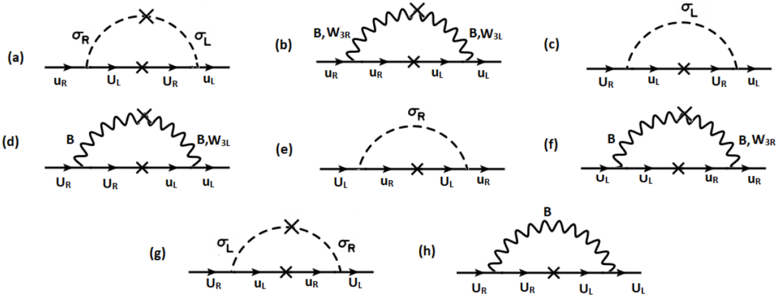
- The corrected mass matrix has a form:

$$\delta\mathcal{M}_U = \begin{bmatrix} \delta M_{LL}^U & \delta M_{LH}^U \\ \delta M_{HL}^U & \delta M_{HH}^U \end{bmatrix}$$

- From here $\overline{\theta}$ can be computed to be:

$$\overline{\theta} = \mathrm{ImTr}\left[-\frac{1}{\kappa_L \kappa_R} \delta M_{LL}^U (Y_U^\dagger)^{-1} M_U Y_U^{-1} + \frac{1}{\kappa_L} \delta M_{LH}^U Y_U^{-1} + \frac{1}{\kappa_R} \delta M_{HL}^U (Y_U^\dagger)^{-1} \right] .$$

Vanishing one-loop $\overline{\theta}$ in left-right symmetry



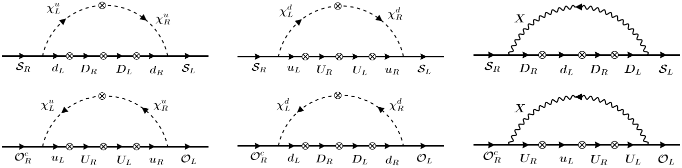
- Each diagram separately gives zero contribution to $\overline{\theta}$
- Induced value of $\overline{\theta}$ at two-loop is of order 10^{-11}
- Such a cancelation is not easy to achieve. For e.g., this typically does not occur in Nelson-Barr type models which utilize *CP* symmetry

New Contributions to $\overline{\theta}$ in Pati-Salam Models

- Pati-Salam models contain new leptoquark gauge boson X_μ, leptoquark scalars $\chi^{u,d}_{L,R}$ as well as color-octet and color-sextet fermions.
- There are new diagrams at one-loop that can contribute to $\overline{\theta}$:

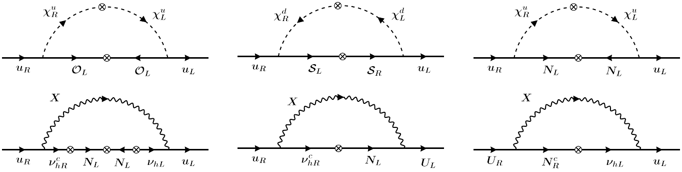
$$\bar{\theta} \;=\; \theta_{\rm QCD} + {\rm ArgDet}(\mathcal{M}_u \mathcal{M}_d) + 5\,{\rm ArgDet}\mathcal{M}_{\mathcal{S}} + 3\,{\rm ArgDet}\mathcal{M}_{\mathcal{O}},$$

- All one-loop corrections to color-octet and color-sextet fermions give zero contribution to $\overline{\theta}$ or is suppressed by $(\kappa_L/\kappa_R)^2 \sim 10^{-23}$



New Contributions to $\overline{\theta}$ in Pati-Salam Models

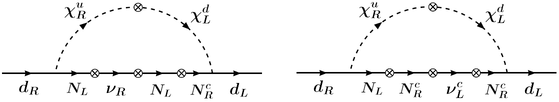
- All one-loop corrections to up-type quark masses yield zero contribution to $\overline{\theta}$:



- The first diagram gives, for e.g.,

$$\mathrm{Im\,Tr}\left[\left(Y_{15}\,M_{15}\,Y_{15}^\dagger\right)\left((Y_{15}^\dagger)^{-1}\,M_{15}^\dagger\,Y_{15}^{-1}\right)\right] = 0$$

- Similarly, most one-loop diagrams from the down-quark sector yield zero to $\overline{\theta}$
- However, down-quark mass corrections through heavy neutrino N generates non-hermitian mass matrix



Estimating $\overline{\theta}$ in Pati-Salam Models

- We have estimated the induced $\overline{\theta}$

$$\bar{\theta} \simeq \frac{\lambda_5}{72} \frac{1}{16\pi^2} \mathrm{Im} \sum_{\alpha=d,s,b} \sum_{i,j} \ell_{ij} \, (Y_{15})_{\alpha j} (Y_{15})^*_{\alpha i}$$

$$\times \left[\left(\frac{\kappa_R}{M_{15,i}} \right)^2 \frac{M_{10,\alpha}}{M_{15,j} y_\alpha^2} (Y_{15}^\dagger Y_{15})_{ji} + \left(\frac{\kappa_R}{M_{15,j}} \right)^2 \frac{M_{10,\alpha}}{M_{15,i} y_\alpha^2} (Y_{15}^T Y_{15}^*)_{ji} \right]$$

- As a benchmark:

$$\mathrm{Input:} \qquad \kappa_R = 5.0 \times 10^{13} \ \mathrm{GeV}, \qquad \lambda_5 = 0.125,$$

$$M_{\chi_R^d} = 6.0 \times 10^{13} \ \mathrm{GeV}, \qquad M_{\chi_L^d} = 7.0 \times 10^{13} \ \mathrm{GeV},$$

$$M_{15} = \mathrm{diag}(5.0 \times 10^{15}, \, 2.5 \times 10^{15}, \, 2.0 \times 10^{14}) \ \mathrm{GeV}, \qquad M_{10} = \mathrm{diag}(10, \, 50, \, 80) \ \mathrm{TeV}$$

$$|\bar{\theta}| \sim (10^{-12} - 10^{-10})$$

- Apart from the loop suppression, $\overline{\theta}$ is suppressed by M_{10}/κ_R
- The color-sextet fermion mass is M_{10}. This implies that the sextet should be in the multi-TeV range
- We have also found solutions where the color-octet is in the multi-TeV range for suppressed $\overline{\theta}$

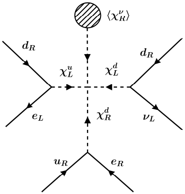
Other Features of the Model

- Baryon number is not conserved in the scalar sector:

$$V(\lambda_6) = 4\lambda_6 \left(\chi_L^{u\alpha}\chi_L^{d\beta}\chi_R^{d\gamma}\chi_R^{\nu}\epsilon_{\alpha\beta\gamma} + \chi_L^{d\alpha}\chi_R^{u\beta}\chi_R^{d\gamma}\chi_L^{\nu}\epsilon_{\alpha\beta\gamma}\right) + \mathrm{h.c.}$$

- Leads to scalar-mediated nucleon decay of the type   Pati (1984)

$$\begin{aligned} n &\rightarrow e^+e^-\nu \\ p &\rightarrow \pi^+\pi^0 e^+e^-\nu \end{aligned}$$



- Amplitude is suppressed, unless scalars have mass of order 100 TeV:

$$A[(\overline{\nu}_L d_R)(\overline{e}_L d_R)(\overline{e^c}_L u_R)] = \frac{4\lambda_6\,\kappa_R}{M_{\chi_L}^4 M_{\chi_R^d}^2}\left(\frac{Y_{10}^2\,\kappa_R}{M_{10}}\right)^2\left(\frac{Y_{15}^2\,\kappa_R}{M_{15}}\right)$$

- Planck suppressed operators leading to $\bar{\theta}$:

$$\mathcal{L}^{(2)}_{\mathrm{gravity}} = \frac{c}{M_{\mathrm{P}}^2} G_{\mu\nu} G_{\alpha\beta}\epsilon^{\mu\nu\alpha\beta}\left(\mathrm{Tr}(H_L^\dagger H_L) - \mathrm{Tr}(H_R^\dagger H_R)\right)$$

- Induced $\bar{\theta} \sim 10^{-10}$ for $v_R \sim 10^{14}$ GeV, and $c \sim 1$

Conclusions

- Parity can solve the strong CP problem without the need for the axion
- Parity solution has been implemented in Pati-Salam models with a universal seesaw
- Realistic quark and lepton masses are obtained, once radiative corrections are included
- Neutrino masses arise as one-loop radiative corrections
- There are new leptoquark-induced diagrams that contribute to $\bar{\theta}$, beyond the left-right models
- Either the color-sextet fermion or the color-octet fermion should be in the multi-TeV range in order to suppress $\overline{\theta}$ sufficiently
- Intriguing connection between neutron EDM, neutrino mass generation and light colored fermions!

Thank you!