Beyond the Standard Model
Neutrino Physics

- Lepton Mixing $V^{PMNS} = O_{23} K_3 O_{13} O_{12} K_{23}$

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(\theta_{23}) & \sin(\theta_{23}) \\ 0 & -\sin(\theta_{23}) & \cos(\theta_{23}) \end{pmatrix}$$

Rotation in the 23-plane

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{i\delta} \end{pmatrix}$$

Dirac Phase

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha} & 0 \\ 0 & 0 & e^{i\beta} \end{pmatrix}$$

Majorana Phases

Standard Paramaterization

New Parametrization

$$V^{PMNS} = O_{23} O_{12} K^{i}_{3} O$$

General orthogonal matrix

$$\begin{pmatrix} 1 & 0 & 0 \\ 0 & i & 0 \\ 0 & 0 & e^{i\alpha} \end{pmatrix}$$

Only one phase to adjust

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Small Neutrino Masses

Neutrino masses are very small compared to other leptons/quarks

Possible explanation, extra right-handed neutrinos $\nu^{\ell}_{R_j}$ and See – Saw mechanism

See - Saw

$$\begin{pmatrix} \nu^{\ell} \\ \ell \end{pmatrix}_{L_i} \in SU(2)_L \qquad \begin{pmatrix} 0 & m \\ m & M \end{pmatrix}$$

$$\nu^{\ell}_{R_j} \qquad |\det| = m^2, \; tr = M \;\Rightarrow\; m_1 \approx m\frac{m}{M} \;,\; m_2 \approx M$$

See – Saw and Non-Unitarity of Lepton Mixing

$$\begin{pmatrix} 0 & m \\ m^T & M \end{pmatrix} \Longrightarrow V = \begin{pmatrix} K & S \\ R & Z \end{pmatrix}$$

Important: How to Parametrize of Non-Unitarity ??

$$V = \begin{pmatrix} K & 0 \\ 0 & Z \end{pmatrix} \begin{pmatrix} 1_{3\times 3} & X^\dagger \\ -X & 1_{3\times 3} \end{pmatrix}$$

Parametrization of Non-Unitarity

Masses $\begin{pmatrix} d & 0 \\ 0 & D \end{pmatrix}$

$$X = i\sqrt{D^{-1}}\; O_c \sqrt{d}$$

$$O_c O_c^T = 1_{3\times 3}$$

Example $O_c = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \sqrt{x^2+1} & ix \\ 0 & -ix & \sqrt{x^2+1} \end{pmatrix}$

Deviations from Unitarity

Parametrized by the eigenvalues $\left(d^2_{X_1}, d^2_{X_2}, d^2_{X_3}\right)$

of $X^\dagger X$

Constraints from fits of twenty eight observables including the W boson mass, the effective mixing weak angle θ_W , several ratios of Z fermionic decays,
the invisible width of the Z, several ratios of weak decays constraining EW universality, weak decays constraining CKM unitarity and some radiative
lepton flavour violating (LFV) processes.