Exploring Strange Origin of Dirac Neutrino Masses at Hadron Colliders

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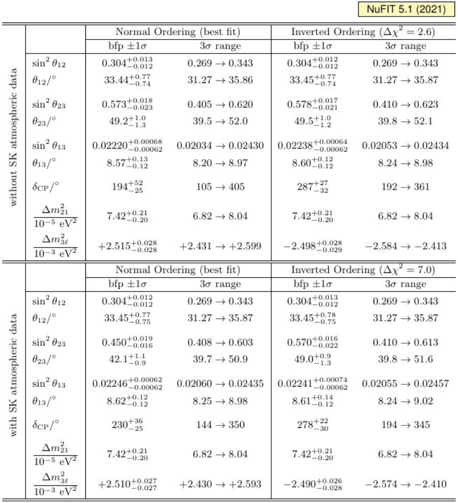
Neutrino Oscillations



NuFIT 5.1 (2021)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.6$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.77}_{-0.74}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.018}_{-0.023}$	$0.405 \to 0.620$	$0.578^{+0.017}_{-0.021}$	$0.410 \to 0.623$
	$\theta_{23}/^\circ$	$49.2^{+1.0}_{-1.3}$	$39.5 \to 52.0$	$49.5^{+1.0}_{-1.2}$	$39.8 \to 52.1$
	$\sin^2\theta_{13}$	$0.02220^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02238^{+0.00064}_{-0.00062}$	$0.02053 \to 0.02434$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{\mathrm{CP}}/^\circ$	194^{+52}_{-25}	$105 \to 405$	287^{+27}_{-32}	$192 \to 361$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.515^{+0.028}_{-0.028}$	$+2.431 \to +2.599$	$-2.498^{+0.028}_{-0.029}$	$-2.584 \to -2.413$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.0$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.45^{+0.77}_{-0.75}$	$31.27 \to 35.87$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.450^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.570^{+0.016}_{-0.022}$	$0.410 \to 0.613$
	$\theta_{23}/^\circ$	$42.1^{+1.1}_{-0.9}$	$39.7 \to 50.9$	$49.0^{+0.9}_{-1.3}$	$39.8 \to 51.6$
	$\sin^2\theta_{13}$	$0.02246^{+0.00062}_{-0.00062}$	$0.02060 \to 0.02435$	$0.02241^{+0.00074}_{-0.00062}$	$0.02055 \to 0.02457$
	$\theta_{13}/^\circ$	$8.62^{+0.12}_{-0.12}$	$8.25 \to 8.98$	$8.61^{+0.14}_{-0.12}$	$8.24 \to 9.02$
	$\delta_{\mathrm{CP}}/^\circ$	230^{+36}_{-25}	$144 \to 350$	278^{+22}_{-30}	$194 \to 345$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.510^{+0.027}_{-0.027}$	$+2.430 \to +2.593$	$-2.490^{+0.026}_{-0.028}$	$-2.574 \to -2.410$

JHEP 09 (2020) 178, www.nu-fit.org

- Neutrino oscillations are well-described by the three-flavor oscillation framework
- Implies that (at least two) neutrino masses are non-zero
- The mass squared differences are sub-eV scale

Neutrino Masses

- "The Standard Model" does not include right-handed singlet neutrino fields, and so has massless neutrinos
  - With right-handed singlet neutrinos, the mass-generating terms would be allowed
- Cosmological bounds place an upper limit on the sum of neutrino masses of ~ 0.12 eV
- Why do neutrinos have such extremely small masses?

A Different Approach to Neutrino Masses

- We will accept the existence of right-handed singlet neutrinos to support Dirac neutrino masses
- The following effective operator, with Standard Model and singlet neutrino fields only, can generate Dirac neutrino mass:

$$O_D = \zeta \frac{[\bar{Q}^i\, s]\epsilon^{ij}[\bar{L}^j\, \nu_R]}{M_D^2} + \mathrm{H.C.} \tag{1}$$

- The light quark condensates $\langle \bar{q} q \rangle \sim -(300\ \mathrm{MeV})^3$ provides EWSB
- Generating ~ 0.1 eV neutrino masses requires $M_D \sim 16$ TeV
  - π^+, K^+ decays to $e^+\nu$ constrain similar scale operators with d and u quarks, thus necessitating the use of the strange quark
- So: how can we generate this sort of operator?

Our 2HDM Model

- We use two Higgs doublets: H_1 and H_2
- H_1 will be the sole doublet that gets a vev
  - It generates quark, charged lepton, W/Z masses exactly as in the SM
  - We'll work in flavor basis with diagonal charged lepton Yukawa couplings
- H_2 will be a heavy doublet that couples only to neutrinos and the strange quark
  - We will call the strange quark Yukawa coupling κ_s
  - For an H_2 mass of M_{H_2}, the mass-basis neutrino Yukawa couplings are

$$\kappa_{\nu,i} = \frac{M_{H_2}^2}{\kappa_s \left\langle \bar{s}s \right\rangle} m_i \tag{2}$$

  - The matrix of neutrino Yukawa couplings is then $V_{PMNS}K_\nu$ with $K_\nu = diag(\kappa_{\nu,1}, \kappa_{\nu,2}, \kappa_{\nu,3})$

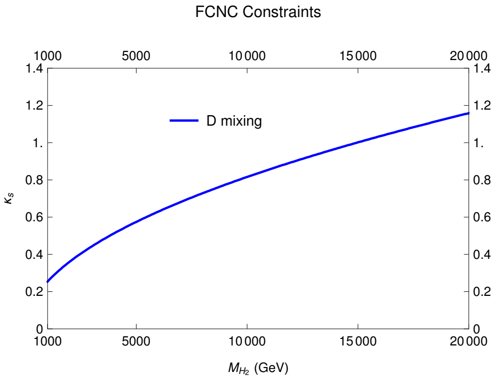
Getting This Flavor Model

- We have the following general 2HDM Yukawa sector (flavor indices suppressed):

$$\sum_{a=1}^{2} \quad -\lambda_u^a \bar{Q}\epsilon H_a^* u - \lambda_d^a \bar{Q} H_a d - \lambda_\nu^a \bar{L}\epsilon H_a^* \nu_R - \lambda_\ell^a \bar{L} H_a \ell + \mathrm{H.C.} \tag{3}$$

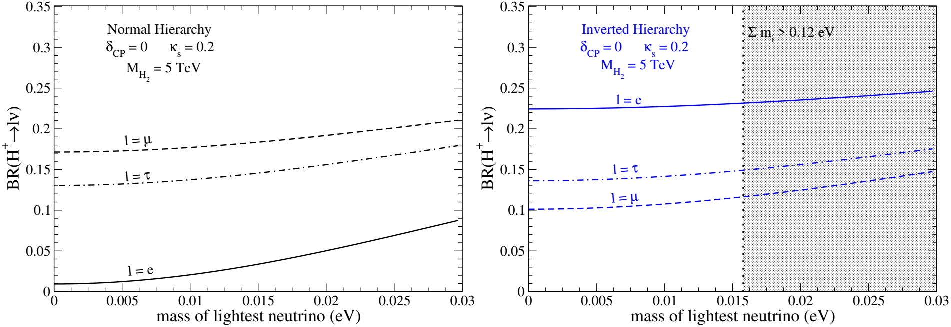
- We introduce a Z_2 symmetry under which H_2 and ν_R are odd, other SM fields are even
  - This Z_2 eliminates neutrino couplings to H_1 and the ordinary fermion mass generation mechanism
  - Also eliminates H_2 couplings to other fermions, including the s quark coupling that we need
- We can spontaneously break the Z_2 with a scalar ϕ, and use a dim 5 operator like $\frac{\phi H_2 \bar{Q} s}{\Lambda}$ where $\langle\phi\rangle \neq 0$
  - This can come from e.g. a UV model with a heavy vector-like quark with the quantum numbers of the right-handed s

Flavor Constraints



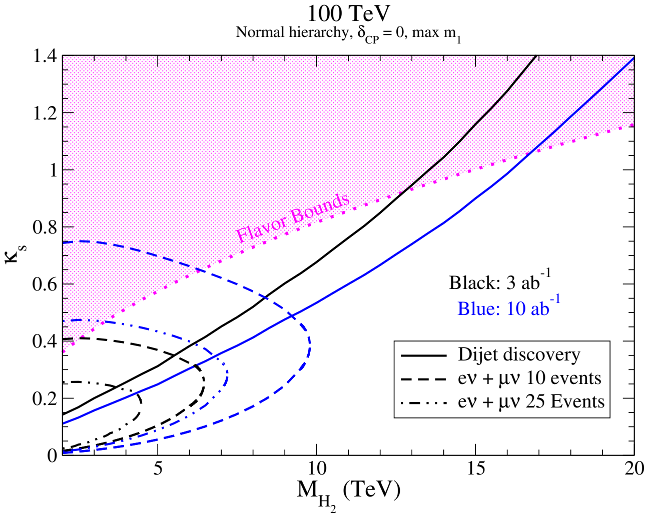
- $D - \bar{D}$ mixing is the primary constraint on κ_s
  - These constraints beat the reach of the LHC; need to go to 100 TeV
- $D_S^+ \to e^+\nu$ can constrain this general mass generating mechanism
  - Current limits come from Belle; we don't expect Belle II to approach sensitivity to our model

Charged Higgs Branching Ratios



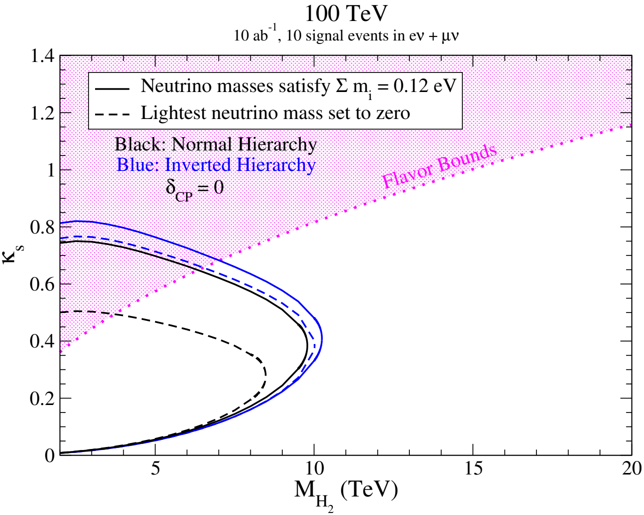
- Charged Higgs can decay to dijet, or charged lepton and neutrino
- The branching ratios $BR(H \to e\nu, \mu\nu, \tau\nu)$ depend on mass hierarchy, slightly on absolute neutrino mass scale
  - In normal hierarchy, $\mu\nu$ is the dominant lepton final state
  - In inverted hierarchy, $e\nu$ is the dominant lepton final state

100 TeV Discovery Potential



- *s* quark coupling leads to large production from quark initial states
- Dijets and $\ell\nu$ provide orthogonal discovery potential

Effects of the Mass Hierarchy



- The neutrino mass hierarchy and absolute mass scale matter for the collider phenomenology

Conclusions

- Chiral condensates in QCD provide another (small) source of electroweak symmetry breaking
- A heavy Higgs doublet can connect this symmetry breaking to the neutrino sector
- Strange quark couplings are a viable path for neutrino mass with interesting collider signatures
  - Dijet signal
  - Lepton plus missing energy
- Charged Higgs branching ratios are sensitive to the neutrino mass hierarchy

Thank you!