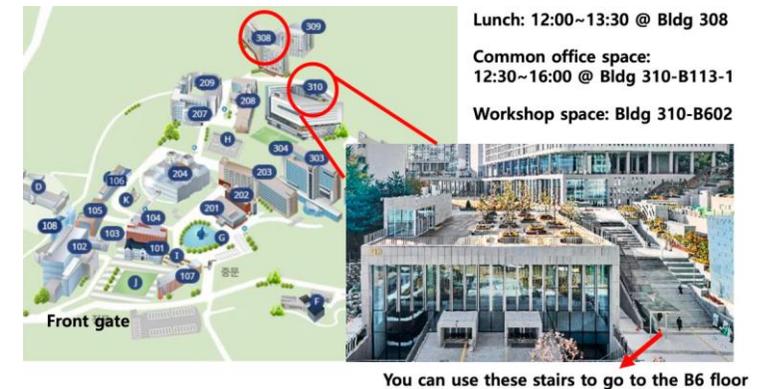# Phenomenology of Dirac neutrino EFT

Based on 2411.17414

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KI∆S KOREA INSTITUTE FOR ADVANCED STUDY

Lunch: 12:00~13:30 @ Bldg 308

Common office space:
12:30~16:00 @ Bldg 310-B113-1

Workshop space: Bldg 310-B602

Front gate

You can use these stairs to go to the B6 floor

Outline

- Construct EFT with RHN assuming neutrinos are Dirac:

  Impose B-L invariance

  <u>Phenomenological studies on $D \leq 6$ BNC & BNV operators</u>

- EWPT; LHC limits from $pp \to l/j + \mathrm{MET}$; Decays of $t, \tau, M \to X + \mathrm{MET}$

- Neutrino masses from effective operators

- Stellar cooling by emitting N

- Contribution to ΔN_{eff}

- Proton decay from BNV operators

Defining Lagrangian

- Introduce $N = N_R$ with B-L charge -1.

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + i\bar{N}\gamma^\mu \partial_\mu N - \left(Y_\nu \bar{L}\tilde{H} N + \mathrm{h.c.}\right) + \frac{1}{\Lambda^2}\sum_i^n C_i^{(6)}\mathcal{O}_i^{(6)}$$

- Assume B-L is a good quantum number and thus N has no Majorana mass.

- Tiny Dirac neutrino Yukawa $Y_\nu = \frac{m_\nu}{\langle H \rangle} \sim 10^{-13}$ may be a consequence of Dirac Seesaw.

BNC operators

$\psi^2 HX$	$\mathcal{O}_{LNB}(+\text{h.c.}) = \overline{L}\sigma^{\mu\nu}N\tilde{H}B_{\mu\nu}$ $\quad$ $\mathcal{O}_{LNW}(+\text{h.c.}) = \overline{L}\sigma^{\mu\nu}N\sigma_I\tilde{H}W^I_{\mu\nu}$
$\psi^2 H^2 D$	$\mathcal{O}_{HN} = \bar{N}\gamma^\mu N(H^\dagger i\overleftrightarrow{D}_\mu H)$ $\quad$ $\mathcal{O}_{HNe}(+\text{h.c.}) = \bar{N}\gamma^\mu e_R(\tilde{H}^\dagger i D_\mu H)$
$\psi^2 H^3$	$\mathcal{O}_{LNH} = \overline{L}\tilde{H}N(H^\dagger H)$
RRRR	$\mathcal{O}_{NN} = (\overline{N}\gamma_\mu N)(\overline{N}\gamma^\mu N)$ $\mathcal{O}_{eeNN} = (\overline{e_R}\gamma_\mu e_R)(\overline{N}\gamma^\mu N)$ $\quad$ $\mathcal{O}_{uuNN} = (\overline{u_R}\gamma_\mu u_R)(\overline{N}\gamma^\mu N)$ $\mathcal{O}_{ddNN} = (\overline{d_R}\gamma_\mu d_R)(\overline{N}\gamma^\mu N)$ $\quad$ $\mathcal{O}_{duNe}(+\text{h.c.}) = (\overline{d_R}\gamma_\mu u_R)(\overline{N}\gamma^\mu e_R)$
LLRR	$\mathcal{O}_{LLNN} = (\overline{L}\gamma_\mu L)(\overline{N}\gamma^\mu N)$ $\quad$ $\mathcal{O}_{QQNN} = (\overline{Q}\gamma_\mu Q)(\overline{N}\gamma^\mu N)$
LRLR	$\mathcal{O}_{LNLe}(+\text{h.c.}) = (\overline{L}N)\epsilon(\overline{L}e_R)$ $\quad$ $\mathcal{O}_{LNQd}(+\text{h.c.}) = (\overline{L}N)\epsilon(\overline{Q}d_R)$ $\mathcal{O}_{LdQN}(+\text{h.c.}) = (\overline{L}d_R)\epsilon(\overline{Q}N)$
LRRL	$\mathcal{O}_{QuNL}(+\text{h.c.}) = (\overline{Q}u_R)(\overline{N}L)$

1612.04527

BNV operators ($B - L = 0$)

$$\mathcal{O}_1 = \left(\overline{d_{\alpha R}{}^c}u_{\beta R}\right)\left(\overline{Q_{i\gamma L}{}^c}L_{jL}\right)\epsilon_{\alpha\beta\gamma}\epsilon_{ij},$$

$$\mathcal{O}_2 = \left(\overline{Q_{i\alpha L}{}^c}Q_{j\beta L}\right)\left(\overline{u_{\gamma R}{}^c}e_R\right)\epsilon_{\alpha\beta\gamma}\epsilon_{ij},$$

$$\mathcal{O}_3 = \left(\overline{Q_{i\alpha L}{}^c}Q_{j\beta L}\right)\left(\overline{Q_{k\gamma L}{}^c}L_{\ell L}\right)\epsilon_{\alpha\beta\gamma}\epsilon_{ij}\epsilon_{k\ell},$$

$$\mathcal{O}_4 = \left(\overline{d_{\alpha R}{}^c}u_{\beta R}\right)\left(\overline{u_{\gamma R}{}^c}e_R\right)\epsilon_{\alpha\beta\gamma}.$$

$$\mathcal{O}_{N1} = \left(\overline{Q_{i\alpha L}{}^c}Q_{j\beta L}\right)\left(\overline{d_{\gamma R}{}^c}N_R\right)\epsilon_{\alpha\beta\gamma}\epsilon_{ij},$$

$$\mathcal{O}_{N2} = \left(\overline{u_{\alpha R}{}^c}d_{\beta R}\right)\left(\overline{d_{\gamma R}{}^c}N_R\right)\epsilon_{\alpha\beta\gamma}.$$

1612.04527

EWPT limits

$$\Gamma^{\mathrm{NP}}(Z \to \mathrm{inv}) = \frac{m_Z^3 v^2}{8\pi\Lambda^4} \left(C_{HN}^2 + 2C_{LNZ}^2 \right),$$

$$\Gamma^{\mathrm{NP}}(h \to \mathrm{inv}) = \frac{3m_h v^4}{16\pi\Lambda^4} C_{LNH}^2,$$

$$\Delta\Gamma(W \to \ell\nu) = \frac{m_W^3 v^2}{48\pi\Lambda^4} C_{HNe}^2$$

$$C = 1$$

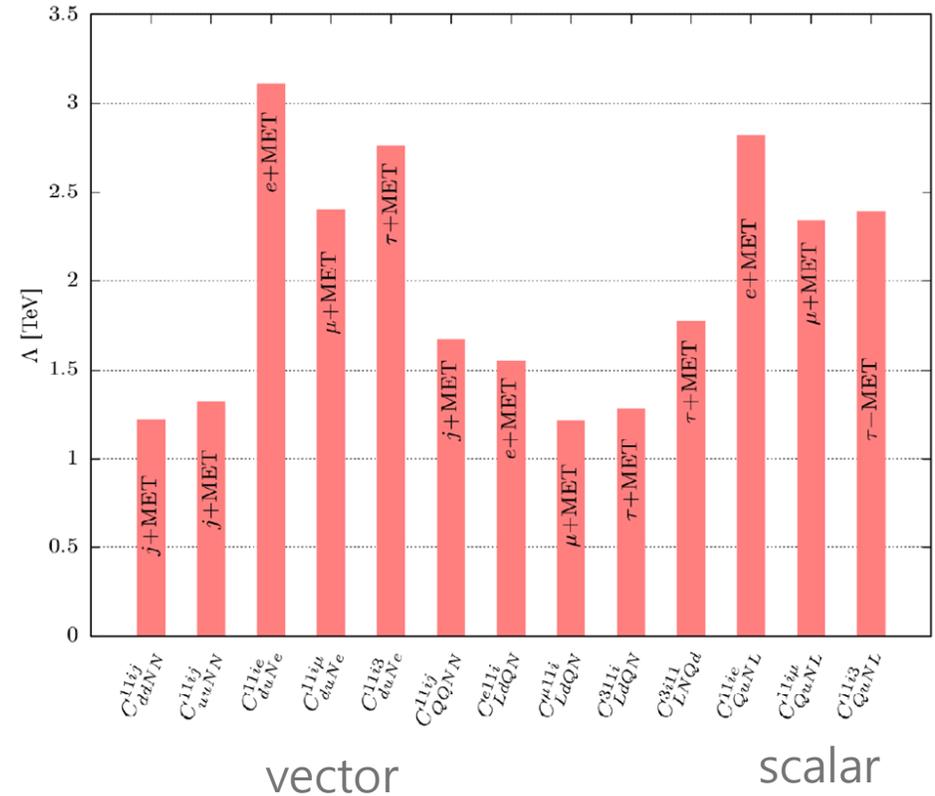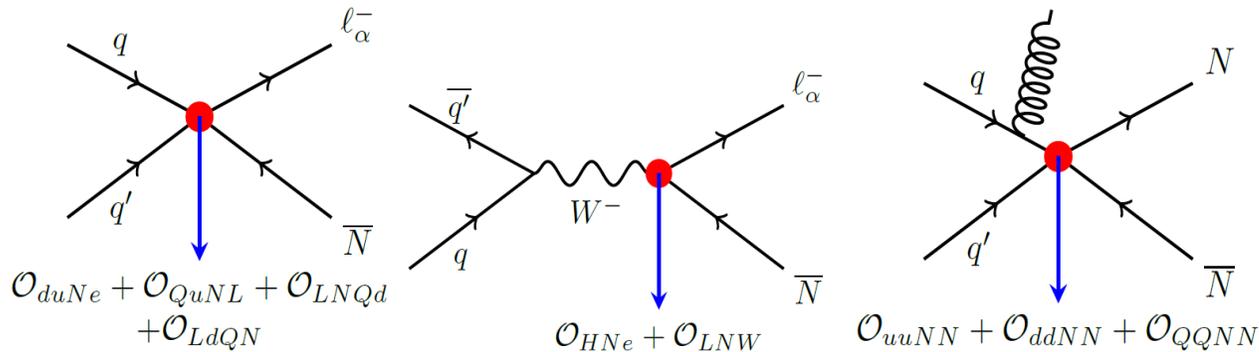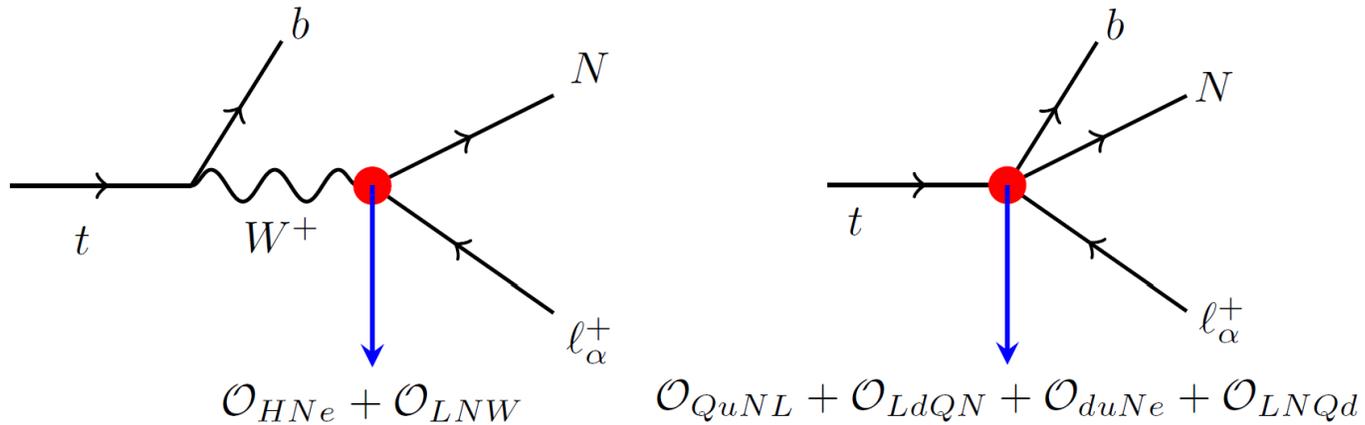$$\Gamma(Z \to \mathrm{inv}) < 2\,\mathrm{MeV} \ \Rightarrow \ \Lambda_{HN,LNZ} > 1\,\mathrm{TeV}$$

$$\mathrm{BR}(h \to \mathrm{inv}) < 10\,\% \ \Rightarrow \ \Lambda_{LNH} > 2.8\,\mathrm{TeV}$$

$$\Delta\Gamma(W \to l\nu) < 2 \times 10^{-3}\Gamma(W \to l\nu) \ \Rightarrow \ \Lambda_{HNe} > 0.58\,\mathrm{TeV}$$

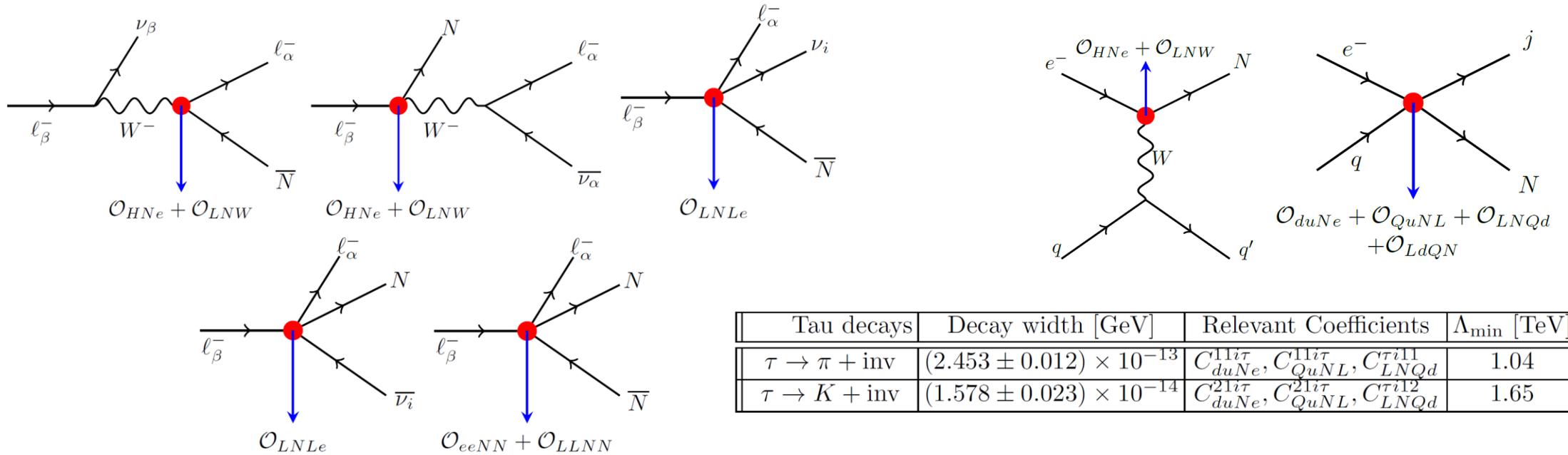# Collider searches: $pp \rightarrow l/j + \mathrm{MET}$

Top decay

$$\mathcal{O}_{HNe} + \mathcal{O}_{LNW}$$

$$\mathcal{O}_{QuNL} + \mathcal{O}_{LdQN} + \mathcal{O}_{duNe} + \mathcal{O}_{LNQd}$$

Top decays	Relevant Coefficients	$\Lambda_{\min}$ [TeV]
$t \to \ell_\alpha b + \mathrm{Inv}$	$C_{HNe}^{i\alpha}, C_{duNe}^{33i\alpha}, C_{LdQN}^{\alpha 33i}, C_{LNQd}^{\alpha i 33}, C_{QuNL}^{33i\alpha}$	0.139, 0.139, 0.137

Meson decay: $M^\pm \to l^\pm N$

$\mathcal{O}_{HNe} + \mathcal{O}_{LNW}$

$\mathcal{O}_{duNe} + \mathcal{O}_{QuNL} + \mathcal{O}_{LNQd}$

Meson decay	Decay width [GeV]	Relevant Coefficients	$\Lambda_{\min}$ [TeV]
$\pi^+ \to \mu^+ \nu_\mu$	$(2.5281 \pm 0.0005) \times 10^{-17}$	$C_{duNe}^{111\mu}, C_{HNe}^{i\mu}, C_{QuNL}^{11i\mu}, C_{LNQd}^{\mu i11}$	2.45
$\pi^+ \to e^+ \nu_e$	$(3.110 \pm 0.010) \times 10^{-21}$	$C_{duNe}^{111e}, C_{HNe}^{ie}, C_{QuNL}^{11ie}, C_{LNQd}^{ei11}$	1.23
$K^+ \to \mu^+ \nu_\mu$	$(3.379 \pm 0.008) \times 10^{-17}$	$C_{duNe}^{21i\mu}, C_{HNe}^{i\mu}, C_{QuNL}^{21i\mu}, C_{LNQd}^{\mu i12}$	1.32
$K^+ \to e^+ \nu_e$	$(8.41 \pm 0.04) \times 10^{-22}$	$C_{duNe}^{21ie}, C_{HNe}^{ie}, C_{QuNL}^{21ie}, C_{LNQd}^{ei12}$	1.12
$D_s^+ \to \mu^+ \nu_\mu$	$(7.09 \pm 0.20) \times 10^{-15}$	$C_{duNe}^{22i\mu}, C_{HNe}^{i\mu}, C_{QuNL}^{22i\mu}, C_{LNQd}^{\mu i22}$	0.73
$D_s^+ \to \tau^+ \nu_\tau$	$(6.95 \pm 0.15) \times 10^{-14}$	$C_{duNe}^{22i\tau}, C_{HNe}^{i\tau}, C_{QuNL}^{22i\tau}, C_{LNQd}^{\tau i22}$	0.77
$B^+ \to \tau^+ \nu_\tau$	$(4.4 \pm 1.0) \times 10^{-17}$	$C_{duNe}^{31i\tau}, C_{HNe}^{i\tau}, C_{QuNL}^{31i\tau}, C_{LNQd}^{\tau i13}$	0.44
$D^+ \to \mu^+ \nu_\mu$	$(2.38 \pm 0.11) \times 10^{-16}$	$C_{duNe}^{12i\mu}, C_{HNe}^{i\mu}, C_{QuNL}^{12i\mu}, C_{LNQd}^{\mu i21}$	0.63
$D^+ \to \tau^+ \nu_\tau$	$(7.6 \pm 1.7) \times 10^{-16}$	$C_{duNe}^{12i\tau}, C_{HNe}^{i\tau}, C_{QuNL}^{12i\tau}, C_{LNQd}^{\tau i21}$	0.72

Tau decay

Tau decays	Decay width [GeV]	Relevant Coefficients	$\Lambda_{\min}$ [TeV]
$\tau \to \pi + \text{inv}$	$(2.453 \pm 0.012) \times 10^{-13}$	$C_{duNe}^{11i\tau}, C_{QuNL}^{11i\tau}, C_{LNQd}^{\tau i11}$	1.04
$\tau \to K + \text{inv}$	$(1.578 \pm 0.023) \times 10^{-14}$	$C_{duNe}^{21i\tau}, C_{QuNL}^{21i\tau}, C_{LNQd}^{\tau i12}$	1.65

Tau decays	Relevant Coefficients	$\Lambda_{\min}$ [TeV]
$\tau^- \to \ell^- + \not{E}$	$C_{HNe}^{i\ell/i\tau}, C_{LNW}^{\ell i/\tau i}, C_{LNLe}^{\tau i\ell(\tau/\ell)}, C_{LNLe}^{\ell i\tau(\tau/\ell)}, C_{LNLe}^{ij(\ell\tau/\tau\ell)}, C_{LNLe}^{\ell j i\tau}, C_{LNLe}^{\tau j i\ell}, C_{eeNN/LLNN}^{\ell\tau ij}$	1.5 (1.49)

Neutrino mass & magnetic moment

- After EWSB, $\mathcal{O}_{LNH}$ and $\mathcal{O}_{LNB/W}$ contribute to neutrino mass and magnetic moment, respectively:

$$\delta m_\nu = C_{LNH}(v)\frac{v^3}{2\sqrt{2}\Lambda^2} \cdot \quad \overset{C=1}{\Rightarrow} \quad \Lambda_{LNH} \gtrsim 2 \times 10^8 \text{ GeV}$$

$$\frac{\mu_{\nu N}}{\mu_B} = \frac{2\sqrt{2}m_e v}{e\Lambda^2}\left(c_w C_{LNB}(v) + s_w C_{LNW}(v)\right) \; < 10^{-12} \; \text{(for } \nu_e \text{ from stellar cooling)}$$

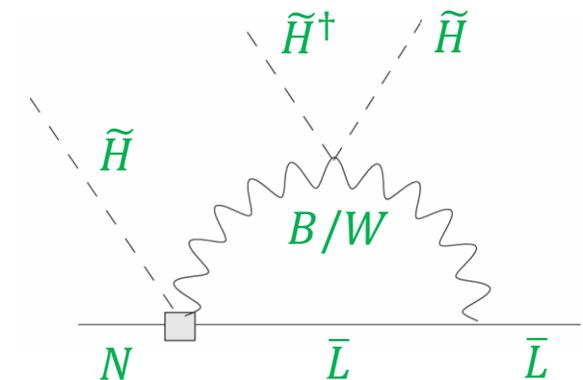$$\overset{C=1}{\Rightarrow} \quad \Lambda_{LNB/W} \gtrsim 10^6 \text{ GeV}$$

Neutrino mass & magnetic moment

- RG running with $C_{LNH}(\Lambda) \equiv 0$ [0504134]:

$$\delta m_\nu = \frac{v^2 e}{8 m_e} \frac{C_{LNH}(v)}{c_w C_{LNB}(v) + s_w C_{LNW}(v)} \frac{\mu_{\nu N}}{\mu_B}$$

$$\frac{\mu_{\nu N}}{\mu_B} \sim 10^{-15} \frac{\delta m_\nu}{0.1 \text{eV}} \Leftrightarrow C_{LNH} \sim 0.02 \, C_{LNB/W} \quad \text{(taking the same cut-off } \Lambda)$$

$$C = 1$$
$$\Rightarrow \quad \Lambda_{LNB/W} \gtrsim 10^7 \text{GeV}$$

Neutrino mass from quark condensate

$$\mathcal{O}_{LNQd}(+\text{h.c.}) = (\overline{L}N)\epsilon(\overline{Q}d_R)$$

$$\mathcal{O}_{QuNL}(+\text{h.c.}) = (\overline{Q}u_R)(\overline{N}L)$$

- $\langle \bar{u}u \rangle = \langle \bar{d}d \rangle = \langle \bar{s}s \rangle = \Lambda_{\text{QCD}}^3 \sim (300\text{MeV})^3$

- Dirac neutrino mass: $m_\nu = \dfrac{\Lambda_{\text{QCD}}^3}{\Lambda^2} \Rightarrow \Lambda_{LNQd,QuNL} \gtrsim 10\text{TeV}$

Stellar cooling

- Neutral current processes: $f \rightarrow fNN(\nu)$ from the $LNLe$ & $ffNN$ $(f = e, u, d, LL, QQ)$ operators

  limiting $\Lambda \gtrsim 4$ TeV.   Raffelt, 9903472

- Charged current processes: $eq \rightarrow q'N$ from the $duNe, LNQd, LdQN, QuNL$ operators

  limiting $\Lambda \gtrsim 70$ TeV.

Contribution to ΔN_{eff}

$$\Delta N_{\text{eff}} = \frac{\sum_\alpha \rho_{N_R}^\alpha}{\rho_{\nu_L}} = 3 \times \frac{\rho_{N_R}}{\rho_{\nu_L}} = 3 \times \left(\frac{T_{N_R}}{T_{\nu_L}}\right)^4$$

- Tracking thermalization of N down to the BBN era.

$$\dot{\rho}_{N_R} + 3H\left(\rho_{N_R} + P_{N_R}\right) = \mathcal{C}_{N_R},$$

$$\mathcal{C}_{N_R} = \int \prod_{\alpha=1}^4 d\Pi_\alpha \, (2\pi)^4 \, \delta^4\left(\mathbf{p}_1 + \mathbf{p}_2 - \mathbf{p}_3 - \mathbf{p}_4\right) \times \overline{|\mathcal{M}|}^2_{N_R + X \to Y + Z}$$

$$T\frac{d\xi_{N_R}}{dT} + (1-\beta)\,\xi_{N_R} = -\frac{\beta}{4\,\kappa\,\xi_{N_R}^3\,H\,T^4}\mathcal{C}_{N_R},$$

$$\left(\exp\left(-\frac{E_3 + E_4}{T}\right)\frac{n_Y}{n_Y^{eq}}\frac{n_Z}{n_Z^{eq}} - \exp\left(-\frac{E_1}{T_{N_R}} - \frac{E_2}{T}\right)\frac{n_{N_R}}{n_{N_R}^{eq}}\frac{n_X}{n_X^{eq}}\right) E_1$$
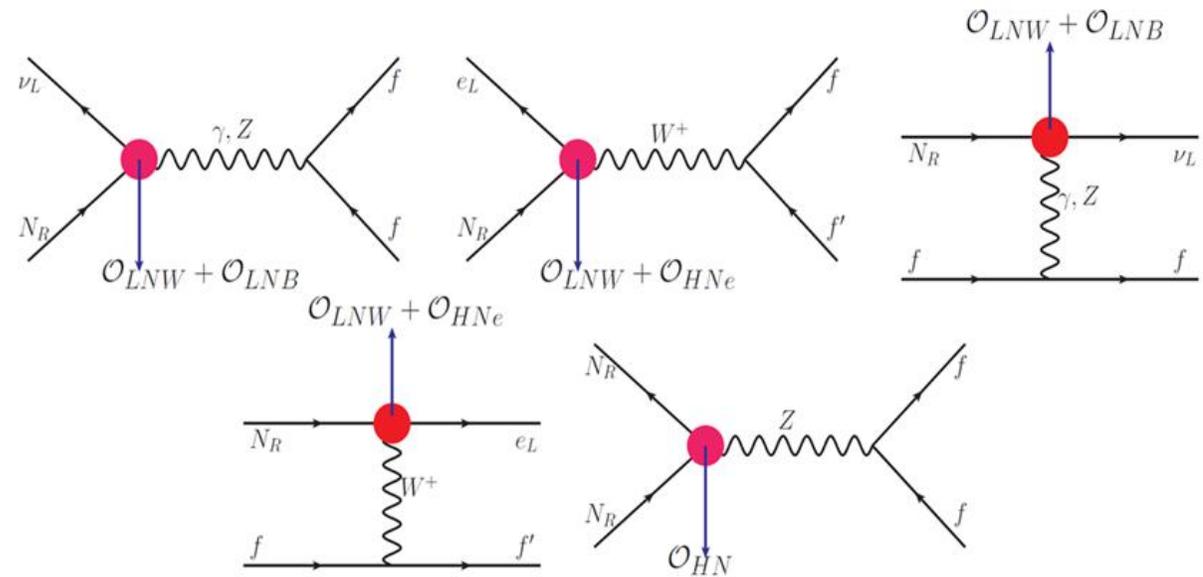
$$\xi_{N_R} \equiv \frac{T_{N_R}}{T_{\nu_L}} \qquad \kappa = 2 \times \frac{7}{8}\frac{\pi^2}{30}$$

$$\beta = \frac{g_\star^{1/2}(T)\sqrt{g_\rho(T)}}{g_s(T)} \qquad g_\star^{1/2} = \frac{g_s}{\sqrt{g_\rho}}\left(1 + \frac{1}{3}\frac{T}{g_s}\frac{dg_s}{dT}\right)$$

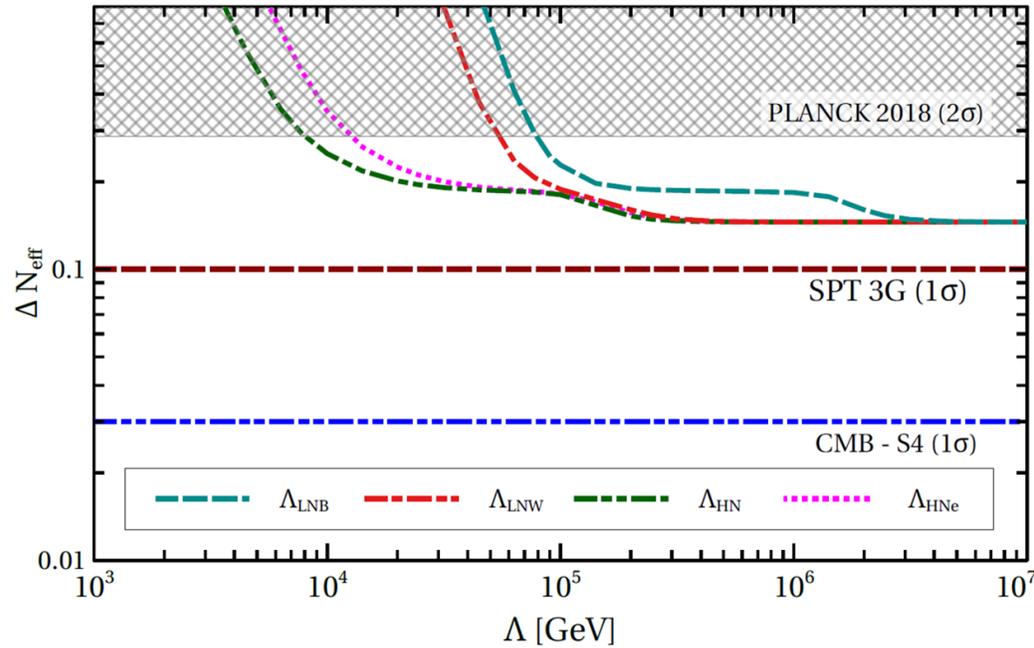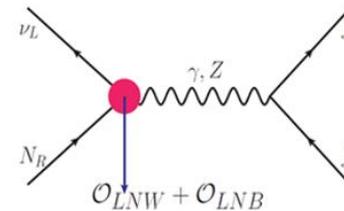# Thermalization processes

Involved Operators	Vertices
Λ_{LNB}	$\frac{v}{\sqrt{2}\Lambda^2_{LNB}}\,\overline{\nu}_L\sigma^{\mu\nu}N_R B_{\mu\nu}$
Λ_{LNW}	$\frac{v}{\sqrt{2}\Lambda^2_{LNW}}\,\overline{\nu}_L\sigma^{\mu\nu}N_R W^3_{\mu\nu}$
Λ_{LNW}	$\frac{v}{\sqrt{2}\Lambda^2_{LNW}}\,\overline{e}_L\sigma^{\mu\nu}N_R\left(W^1_{\mu\nu}+iW^2_{\mu\nu}\right)$
Λ_{HNe}	$-\frac{v^2 g_L}{\sqrt{2}\Lambda^2_{HNe}}\,\overline{N}_R\gamma^{\mu}e_R W^+_{\mu}$
Λ_{HN}	$\frac{v^2 g_L}{2C_W\Lambda^2_{HN}}\,\overline{N}_R\gamma^{\mu}N_R Z_{\mu}$

ΔN_{eff} limits

Cut-off scale	Constraint from N_{eff} (TeV)
Λ_{LNB}	80
Λ_{LNW}	50
Λ_{HNe}	15
Λ_{HN}	8

$$\sigma(eN \to e\nu) \propto \left(2\left(2m_A^2 + s\right)\log\left(\frac{m_A^2 + s}{m_A^2}\right) - 4s\right) \quad m_A^2 = \frac{e^2 T^2}{6}$$

BNV operators ($B - L = 0$)

$$\mathcal{O}_1 = \left(\overline{d_{\alpha R}{}^c} u_{\beta R} \right) \left(\overline{Q_{i\gamma L}{}^c} L_{jL} \right) \epsilon_{\alpha\beta\gamma} \epsilon_{ij},$$

$$\mathcal{O}_2 = \left(\overline{Q_{i\alpha L}{}^c} Q_{j\beta L} \right) \left(\overline{u_{\gamma R}{}^c} e_R \right) \epsilon_{\alpha\beta\gamma} \epsilon_{ij},$$

$$\mathcal{O}_3 = \left(\overline{Q_{i\alpha L}{}^c} Q_{j\beta L} \right) \left(\overline{Q_{k\gamma L}{}^c} L_{\ell L} \right) \epsilon_{\alpha\beta\gamma} \epsilon_{ij} \epsilon_{k\ell},$$

$$\mathcal{O}_4 = \left(\overline{d_{\alpha R}{}^c} u_{\beta R} \right) \left(\overline{u_{\gamma R}{}^c} e_R \right) \epsilon_{\alpha\beta\gamma}.$$

$$\mathcal{O}_{N1} = \left(\overline{Q_{i\alpha L}{}^c} Q_{j\beta L} \right) \left(\overline{d_{\gamma R}{}^c} N_R \right) \epsilon_{\alpha\beta\gamma} \epsilon_{ij}, \qquad \text{1612.04527}$$

$$\mathcal{O}_{N2} = \left(\overline{u_{\alpha R}{}^c} d_{\beta R} \right) \left(\overline{d_{\gamma R}{}^c} N_R \right) \epsilon_{\alpha\beta\gamma}.$$

Proton decay

- Nucleon transition to meson+lepton induced by BNV operators:

$$\overline{v_\ell^c}(\vec{q},s)\langle P(\vec{p})|\,\mathcal{O}^{\chi L}\,|N(\vec{k},s)\rangle = \overline{v_\ell^c}(q,s)P_L\left[W_0^\chi(Q^2) - \frac{i\slashed{q}}{m_N}W_1^\chi(Q^2)\right]u_N(k,s)$$

$$Q^2 = -q^2 = -(E_N - E_P)^2 + (\vec{k} - \vec{p})^2$$

$$\Gamma(N \to P\bar{\ell}) = \frac{1}{32\pi m_N}\lambda^{\frac{1}{2}}\left(1, \frac{m_\ell^2}{m_N^2}, \frac{m_P^2}{m_N^2}\right)\left((m_\ell^2 + m_N^2 - m_P^2)\left(|\tilde{W}_0|^2 + \frac{m_\ell^2}{m_N^2}|\tilde{W}_1|^2\right) - 4m_\ell^2\mathrm{Im}\left(\tilde{W}_0\tilde{W}_1^*\right)\right)$$

$$\tilde{W}_{0,1} = \sum_I \frac{C^I}{\Lambda^2}W_{0,1}^I(N \to P).$$
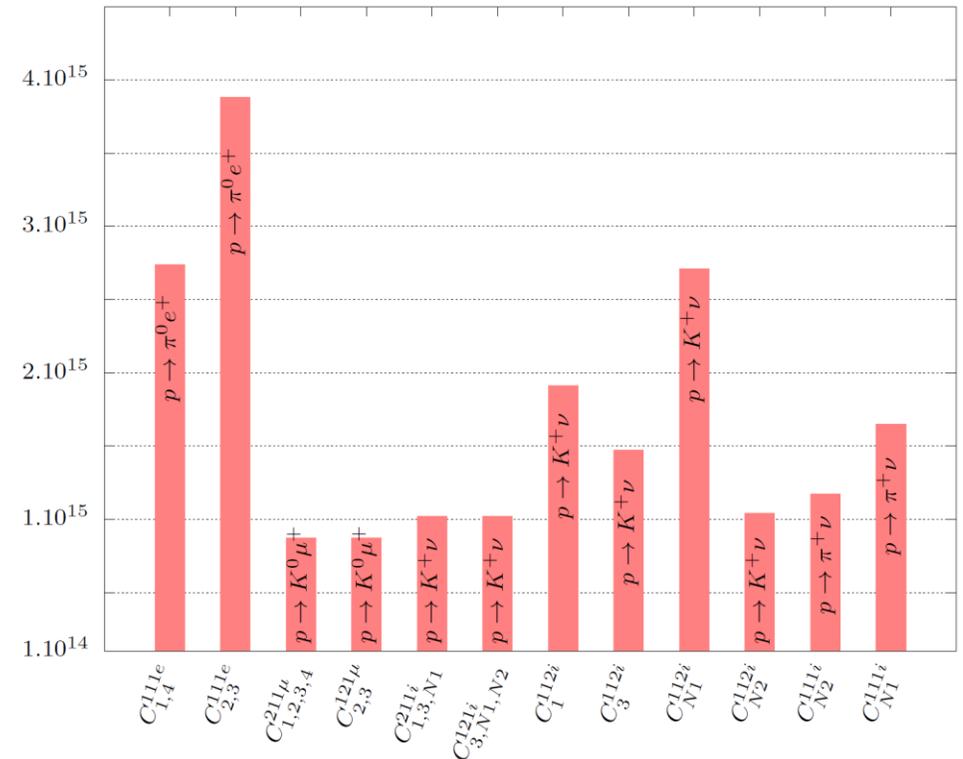
Form factors [2111.01608]

$$\mathcal{O}_1 = \left(\overline{d_{\alpha R}{}^c} u_{\beta R}\right)\left(\overline{Q_{i\gamma L}{}^c} L_{jL}\right)\epsilon_{\alpha\beta\gamma}\epsilon_{ij},$$

$$\mathcal{O}_2 = \left(\overline{Q_{i\alpha L}{}^c} Q_{j\beta L}\right)\left(\overline{u_{\gamma R}{}^c} e_R\right)\epsilon_{\alpha\beta\gamma}\epsilon_{ij},$$

$$\mathcal{O}_3 = \left(\overline{Q_{i\alpha L}{}^c} Q_{j\beta L}\right)\left(\overline{Q_{k\gamma L}{}^c} L_{\ell L}\right)\epsilon_{\alpha\beta\gamma}\epsilon_{ij}\epsilon_{k\ell},$$

$$\mathcal{O}_4 = \left(\overline{d_{\alpha R}{}^c} u_{\beta R}\right)\left(\overline{u_{\gamma R}{}^c} e_R\right)\epsilon_{\alpha\beta\gamma}.$$

$$\mathcal{O}_{N1} = \left(\overline{Q_{i\alpha L}{}^c} Q_{j\beta L}\right)\left(\overline{d_{\gamma R}{}^c} N_R\right)\epsilon_{\alpha\beta\gamma}\epsilon_{ij},$$

$$\mathcal{O}_{N2} = \left(\overline{u_{\alpha R}{}^c} d_{\beta R}\right)\left(\overline{d_{\gamma R}{}^c} N_R\right)\epsilon_{\alpha\beta\gamma}.$$

Matrix element	W_0	W_1
$\langle\pi^+\lvert (ud)_L d_L \lvert p\rangle$	0.1032	−0.130
	0.105	−0.132
$\langle\pi^+\lvert (ud)_R d_L \lvert p\rangle$	−0.1125	0.116
	−0.1139	0.118
$\langle K^0\lvert (us)_L u_L \lvert p\rangle$	0.0395	0.0256
	0.0397	0.0254
$\langle K^0\lvert (us)_R u_L \lvert p\rangle$	0.0688	−0.0250
	0.0693	−0.0254
$\langle K^+\lvert (us)_L d_L \lvert p\rangle$	0.0263	−0.0448
	0.0266	−0.0453
$\langle K^+\lvert (us)_R d_L \lvert p\rangle$	−0.0301	0.0452
	−0.0307	0.0458
$\langle K^+\lvert (ud)_L s_L \lvert p\rangle$	0.0923	−0.0638
	0.0932	−0.0653
$\langle K^+\lvert (ud)_R s_L \lvert p\rangle$	−0.0835	0.0588
	−0.0846	0.0605
$\langle K^+\lvert (ds)_L u_L \lvert p\rangle$	−0.0651	0.0192
	−0.0658	0.0201
$\langle K^+\lvert (ds)_R u_L \lvert p\rangle$	−0.0394	−0.0203
	−0.0393	−0.0204

$$\langle\pi^0\lvert (ud)_\chi u_L \lvert p\rangle = \sqrt{2}\langle\pi^+\lvert (ud)_\chi d_L\lvert p\rangle$$

Nucleon decay limits: $p \to \pi^+/K^+ + N$

Process	τ (10^{33} years)	operators	$\Lambda_{\min}$ [10^{15} GeV]
$p \to \pi^0 e^+$ ($\pi^0 \mu^+$)	24 (16) [58]	$C^{111\ell}_{1,2,3,4}$	3.88 (3.52)
$n \to \pi^- e^+$ ($\pi^- \mu^+$)	5.3 (3.5) [59]		2.66 (2.41)
$p \to \eta^0 e^+$ ($\eta^0 \mu^+$)	10 (4.7) [59]	$C^{111\ell}_{1,2,3,4}$	2.56 (2.12)
$n \to \eta^0 \nu$	0.158 [60]	$C^{111\ell}_{1,3}$, $C^{111i}_{N1,N2}$	0.9
$p \to K^+ \nu$	6.61 [61]	$C^{211i}_{1,3,N1}, C^{112i}_{1,3,N1,N2}, C^{121i}_{3,N1,N2}$	3.46
$n \to K^0 \nu$	0.13 [62]		1.3
$p \to K^0 e^+$ ($K^0 \mu^+$)	1 (1.6) [63, 64]	$C^{211\ell}_{1,2,3,4}, C^{121\ell}_{2,3}$	1.1 (1.23)
$p \to \pi^+ \nu$	0.39 [62]	$C^{111i}_{1,3,N1,N2}$	1.64
$n \to \pi^0 \nu$	1.1 [62]		2.14

Cf) Flavor dependent limits, e.g., $t^c b^c s^c N$ (?)

Conclusion

- Study of Dirac neutrino EFT (B-L invariance with RHN N).
- RHN appears as MET in collider searches: $\Lambda_{\mathrm{relevant}} \gtrsim O(\mathrm{TeV})$.
- Neutrino mass generation:

  $\Lambda_{LNH} \gtrsim 10^8 \mathrm{GeV}, \; \Lambda_{LNB/W} \gtrsim 10^7 \mathrm{GeV}, \; \Lambda_{LNQd,QuNL} \gtrsim 10^4 \; \mathrm{GeV}.$

- Stellar cooling: $\Lambda_{(ffNN,LNLe;\; duNe,LNQd,LdQN,QuNL)} \gtrsim (4\,;70)\mathrm{TeV}$
- ΔN_{eff} limits: $\Lambda_{HNe,HN} \gtrsim \mathrm{TeV}, \; \Lambda_{LNB(W)} \gtrsim 8(5) \; \mathrm{TeV}.$
- Proton decays to RHN: $\Lambda_{N1,2}^{(u,d,s)} \gtrsim 10^{15} \mathrm{GeV}$ (extendable to general flavor structure).