# 中微子理论进展汇报

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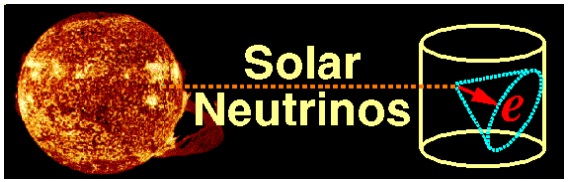
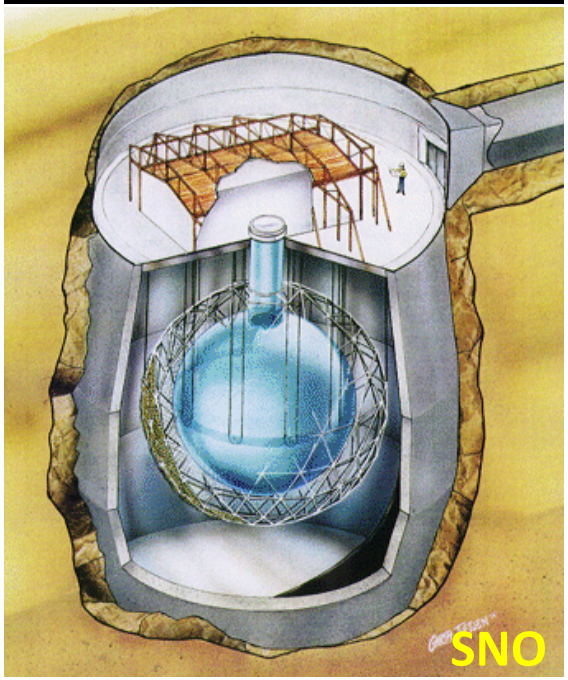
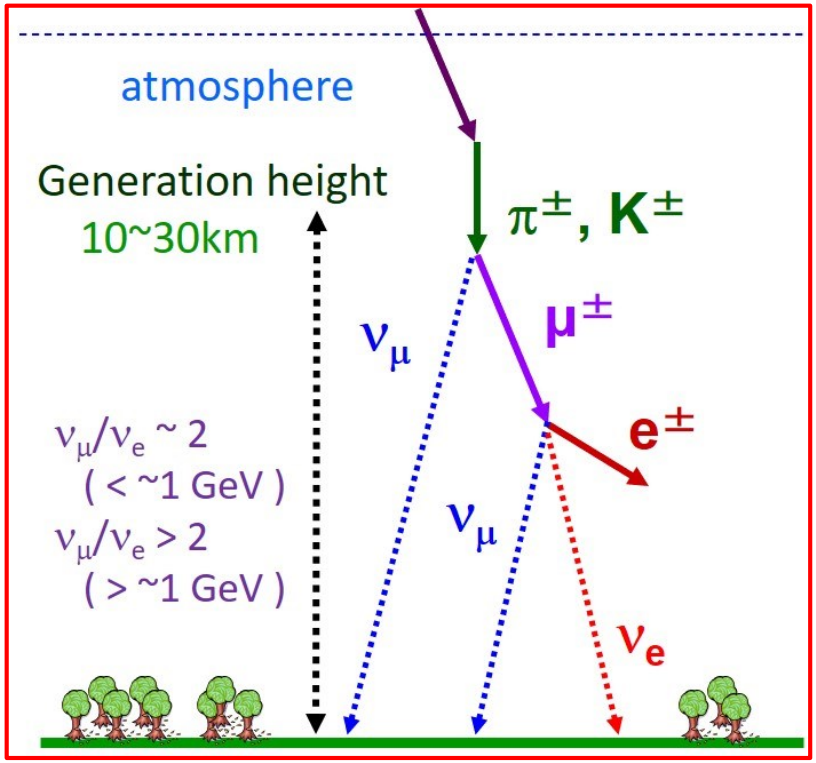
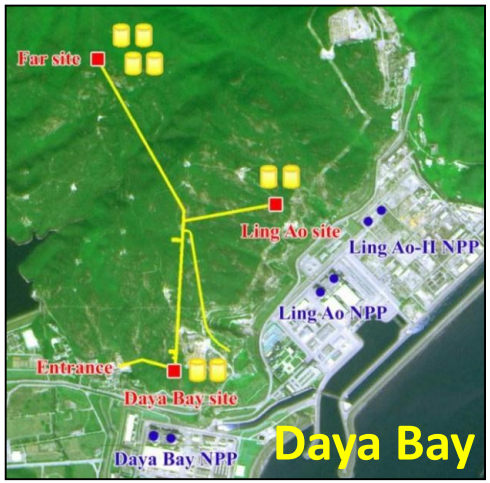
# Massive Neutrinos: New Physics beyond the SM

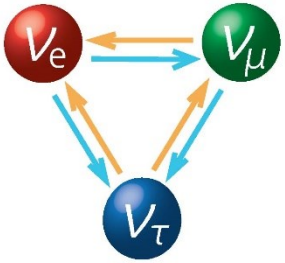




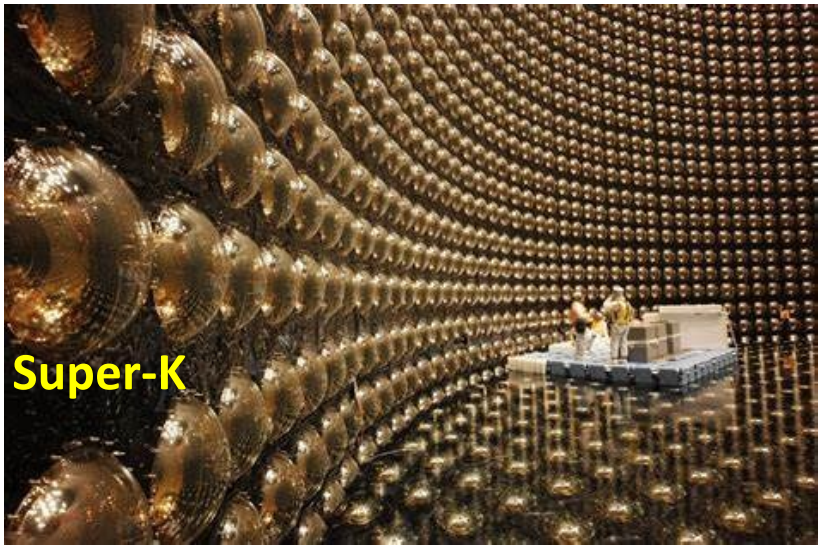




**Nobel Prize in 2015**




- **Neutrinos are massive !!!**
- **New physics beyond the SM**

# Current Status of Neutrino Oscillations

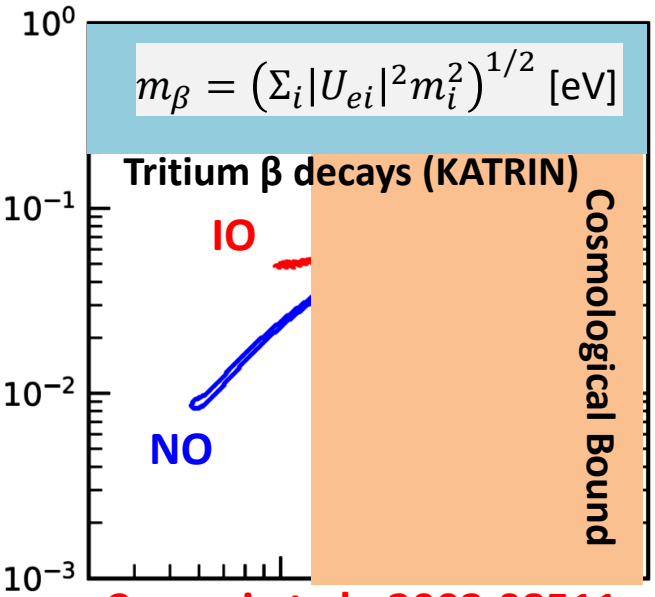
**Basic neutrino parameters** Esteban *et al.*, 2007.14792, NuFIT 5.0 (2020)

| without SK atmospheric data | Normal Ordering (best fit) | | Inverted Ordering ($\Delta\chi^2 = 2.7$) | |
|---|---|---|---|---|
| | bfp $\pm 1\sigma$ | $3\sigma$ range | bfp $\pm 1\sigma$ | $3\sigma$ range |
| $\sin^2\theta_{12}$ | $0.304^{+0.013}_{-0.012}$ | $0.269 \to 0.343$ | $0.304^{+0.013}_{-0.012}$ | $0.269 \to 0.343$ |
| $\theta_{12}/^\circ$ | $33.44^{+0.78}_{-0.75}$ | $31.27 \to 35.86$ | $33.45^{+0.78}_{-0.75}$ | $31.27 \to 35.87$ |
| $\sin^2\theta_{23}$ | $0.570^{+0.018}_{-0.024}$ | $0.407 \to 0.618$ | $0.575^{+0.017}_{-0.021}$ | $0.411 \to 0.621$ |
| $\theta_{23}/^\circ$ | $49.0^{+1.1}_{-1.4}$ | $39.6 \to 51.8$ | $49.3^{+1.0}_{-1.2}$ | $39.9 \to 52.0$ |
| $\sin^2\theta_{13}$ | $0.02221^{+0.00068}_{-0.00062}$ | $0.02034 \to 0.02430$ | $0.02240^{+0.00062}_{-0.00062}$ | $0.02053 \to 0.02436$ |
| $\theta_{13}/^\circ$ | $8.57^{+0.13}_{-0.12}$ | $8.20 \to 8.97$ | $8.61^{+0.12}_{-0.12}$ | $8.24 \to 8.98$ |
| $\delta_{CP}/^\circ$ | $195^{+51}_{-25}$ | $107 \to 403$ | $286^{+27}_{-32}$ | $192 \to 360$ |
| $\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$ | $7.42^{+0.21}_{-0.20}$ | $6.82 \to 8.04$ | $7.42^{+0.21}_{-0.20}$ | $6.82 \to 8.04$ |
| $\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$ | $+2.514^{+0.028}_{-0.027}$ | $+2.431 \to +2.598$ | $-2.497^{+0.028}_{-0.028}$ | $-2.583 \to -2.412$ |

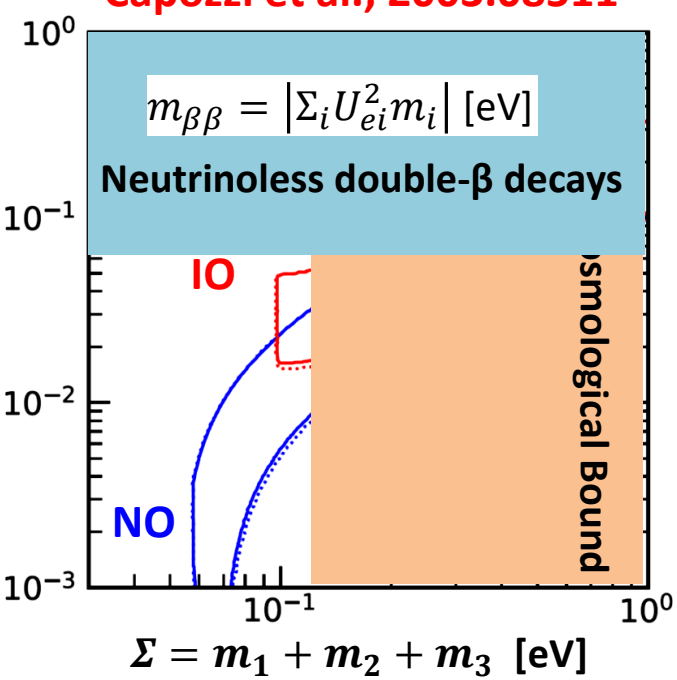
- **Future neutrino oscillation experiments will measure the octant of $\theta_{23}$, the CP-violating phase $\delta$, and the neutrino mass ordering**
- **The most restrictive bound on absolute neutrino masses is coming from cosmological observations: $m_1 + m_2 + m_3 < 0.12$ eV (Planck)**

# Current Status of Absolute Neutrino Masses






Capozzi et al., 2003.08511

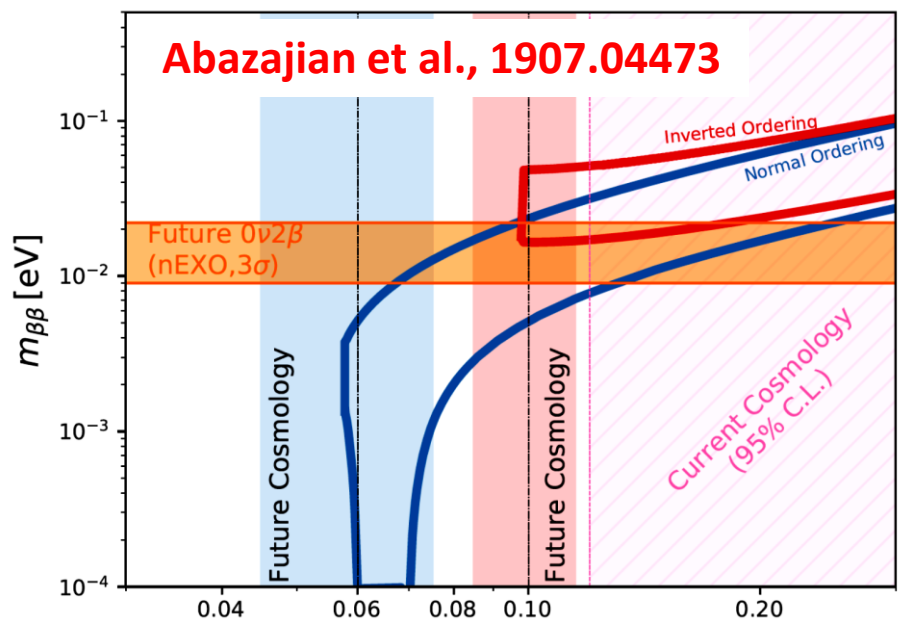



$m_1 < m_2 < m_3$ (NO) or $m_3 < m_1 < m_2$ (IO)

**Constraints on absolute neutrino masses**

- **Tritium β decays (95% C.L.)**
  $m_\beta < 0.8$ eV (KATRIN 2021)
- **Neutrinoless double-β decays (90% C.L.)**
  $m_{\beta\beta} < (0.036 \sim 0.156)$ eV (KamLAND-Zen)
  $(0.15 \sim 0.40)$ eV (EXO-200)
  $(0.08 \sim 0.18)$ eV (GERDA-II)
  $(0.08 \sim 0.35)$ eV (CUORE)
- **Cosmological observations (95% probability)**
  $\Sigma < 0.12$ eV (Planck)

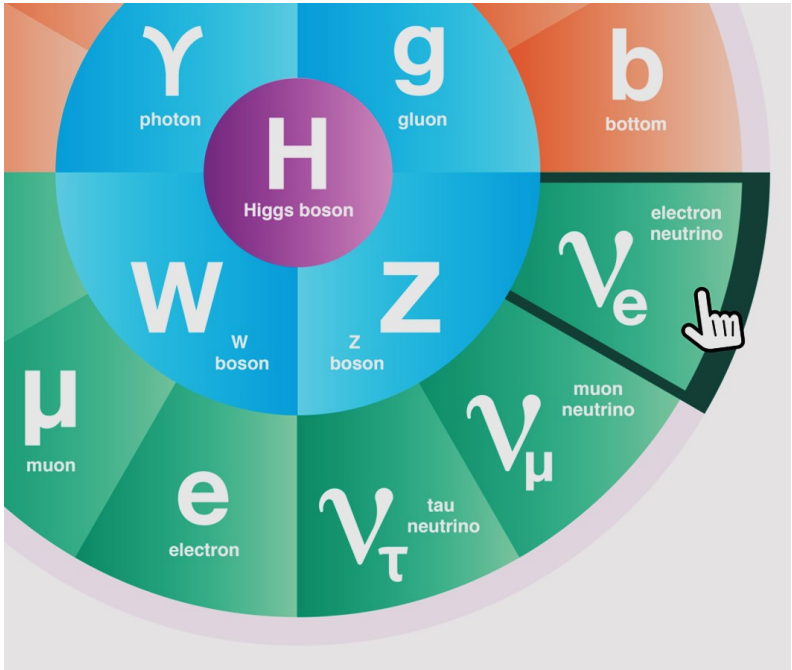
Abazajian et al., 1907.04473



# Open Questions in Neutrino Physics



- Normal or Inverted (sign of $\Delta m^2_{31}$?)
- Leptonic CP Violation (δ = ?)
- Octant of $\theta_{23}$ (> or < 45°?)
- Absolute Neutrino Masses ($m_{\text{lightest}} = 0$?)
- Majorana or Dirac Nature ($\nu=\nu^c$ ?)
- Majorana CP-Violating Phases (how?)




- Extra Neutrino Species
- Exotic Neutrino Interactions
- Various LNV & LFV Processes
- Leptonic Unitarity Violation

- Origin of Neutrino Masses
- Flavor Structure (Symmetry?)
- Quark-Lepton Connection
- Relations to DM and/or BAU

# Zero Neutrino Masses in the SM

## Unified Electroweak Theory with the $SU(2)_L x U(1)_Y$ gauge symmetry

- **Particle content**
  ***minimality***
- **Symmetries**
  ***SU(2)xU(1)***
- **Renormalizability**
  ***predictive power***

| Particle content | Weak isospin $I^3$ | Hypercharge $Y$ | Electric charge $Q$ |
|---|---|---|---|
| $Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix}$ | $\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$ | $+1/6$ | $\begin{pmatrix} +2/3 \\ -1/3 \end{pmatrix}$ |
| $\ell_L \equiv \begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$ | $\begin{pmatrix} +1/2 \\ -1/2 \end{pmatrix}$ | $-1/2$ | $\begin{pmatrix} 0 \\ -1 \end{pmatrix}$ |
| $U_R \equiv u_R,\ c_R,\ t_R$ | $0$ | $+2/3$ | $+2/3$ |
| $D_R \equiv d_R,\ s_R,\ b_R$ | $0$ | $-1/3$ | $-1/3$ |
| $E_R \equiv e_R,\ \mu_R,\ \tau_R$ | $0$ | $-1$ | $-1$ |

**Glashow, 61; Weinberg, 67; Salam, 68**

**The reason is rather SIMPLE** **NO right-handed neutrinos**

- **Neutrinos experience only the weak force**
- **Weak interactions violate parity**
- **Only LH neutrinos/RH antineutrinos in weak interactions**

**But neutrino oscillations show that neutrinos are massive particles**

# The simplest way to accommodate tiny neutrino masses

- **Dirac Neutrinos**
- **Majorana Neutrinos**

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \overline{\nu_{\rm R}} {\rm i}\partial\!\!\!/ \nu_{\rm R} - \left[\overline{\ell_{\rm L}} Y_\nu \tilde{H} \nu_{\rm R} + {\rm h.c.}\right] - \left[\frac{1}{2}\overline{\nu_{\rm R}^{\rm C}} M_{\rm R} \nu_{\rm R} + {\rm h.c.}\right]$$

**Generate Dirac ν masses in a similar way to that for quarks and charged leptons, after the spontaneous gauge symmetry breaking**

$$M_\nu = Y_\nu v$$

$v \approx 174$ GeV

$M_\nu$: $O(0.1\ \text{eV})$

$Y_\nu$: $O(10^{-12})$

**Generate tiny Majorana ν masses via the so-called seesaw mechanism**

$$M_\nu = v^2 Y_\nu M_{\rm R}^{-1} Y_\nu^{\rm T}$$

$M_\nu$: $O(0.1\ \text{eV})$

$M_{\rm R}$: $O(10^{14}\ \text{GeV})$

## Difficulties with Dirac neutrinos

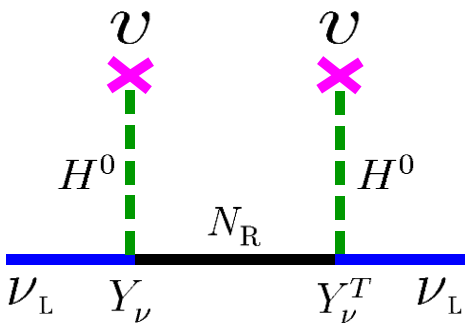
- **Tiny Dirac masses worsen fermion mass hierarchy problem (i.e., $m_i/m_t < 10^{-12}$)**
- **Mandatory lepton number conservation, which is actually accidental in the SM**

- **Retain the SM symmetries**
- **Well motivated by GUTs**

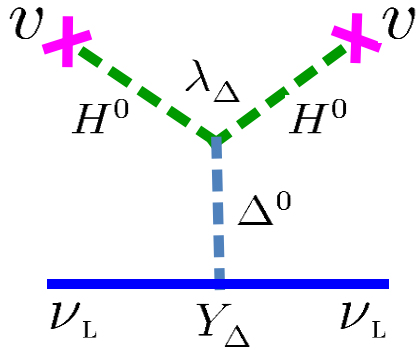
**All the terms allowed by the SM gauge symmetries**

# Origin of Neutrino Masses

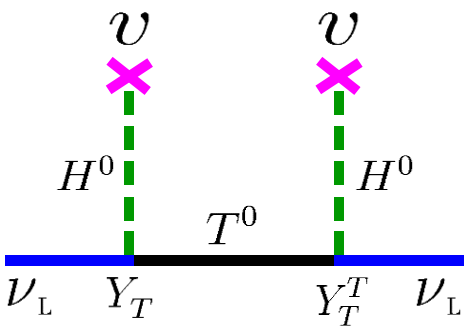
## Majorana neutrinos: a natural way to understand neutrino masses




$$M_\nu \approx -v^2 Y_\nu \frac{1}{M_R} Y_\nu^T$$




$$M_\nu \approx \lambda_\Delta Y_\Delta \frac{v^2}{M_\Delta}$$




$$M_\nu \approx -v^2 Y_T \frac{1}{M_T} Y_T^T$$

**Type-I: SM + 3 right-handed Majorana ν's (Minkowski 77; Yanagida 79; Glashow 79; Gell-Mann, Ramond, Slansky 79; Mohapatra, Senjanovic 79)**

**Type-II: SM + 1 Higgs triplet (Magg, Wetterich 80; Schechter, Valle 80; Lazarides et al 80; Mohapatra, Senjanovic 80; Gelmini, Roncadelli 80)**

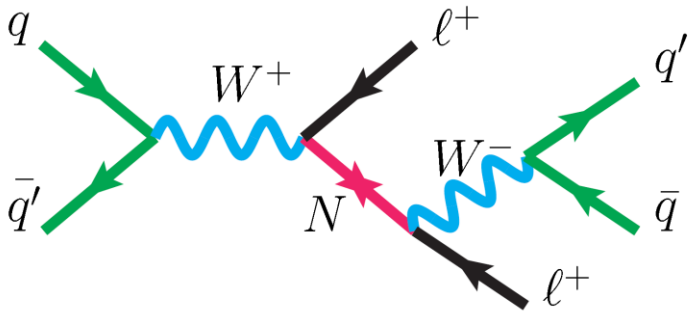
**Type-III: SM + 3 triplet fermions (Foot, Lew, He, Joshi 89)**

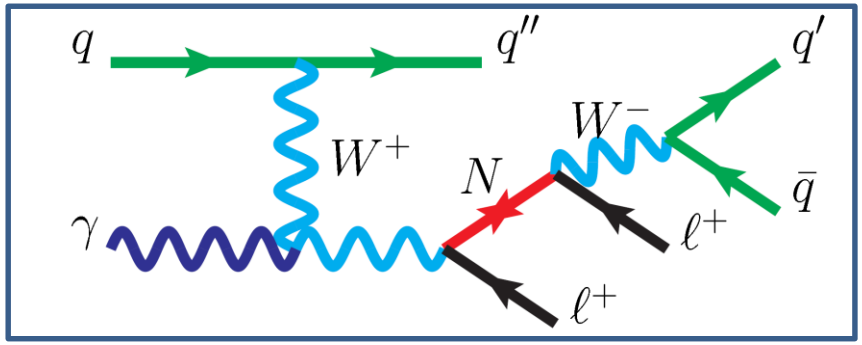
- **Can naturally be embedded into the Grand Unified Theories, e.g., SO(10) GUT**
- **Responsible for both tiny neutrino masses and matter-antimatter asymmetry**

# A: Collider Tests of Low-Scale Seesaw Models



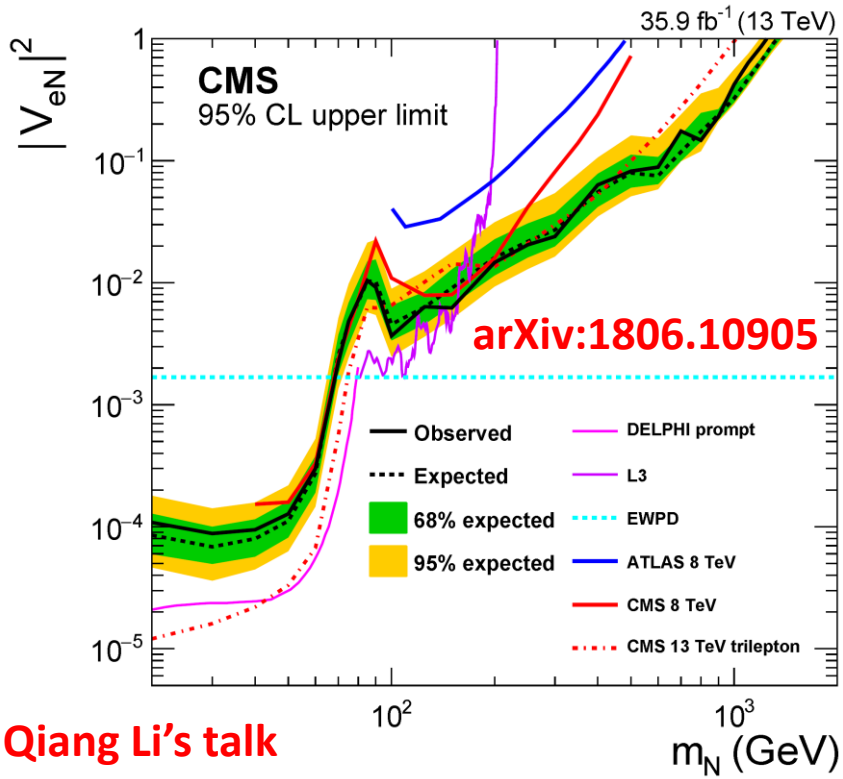
- **Experimental searches for heavy Majorana neutrinos from type-I seesaw**



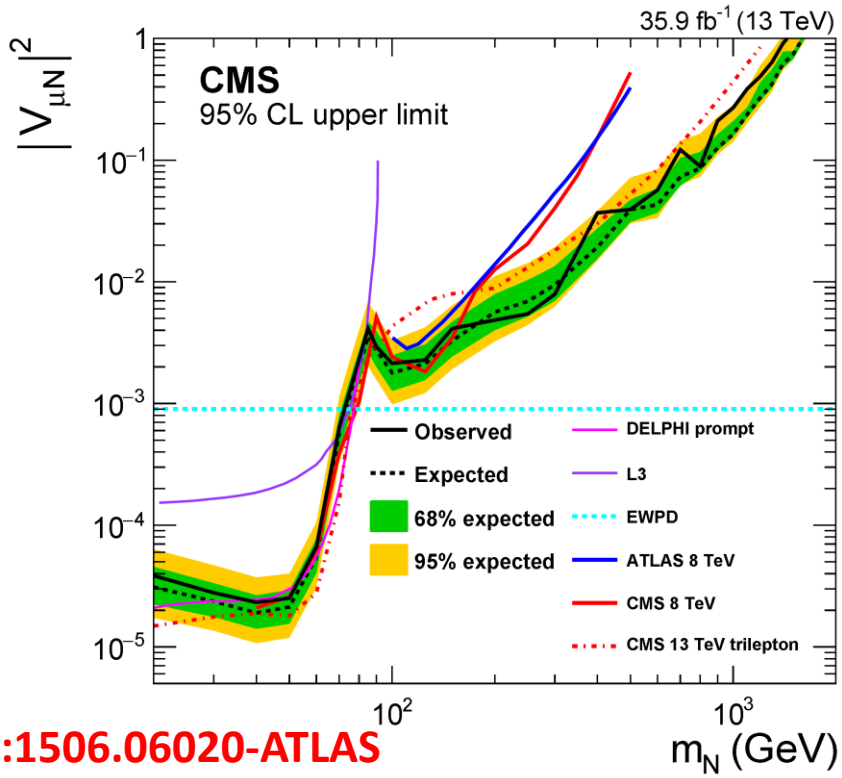




Cai, Han, Li, Ruiz, Front. in Phys. 6 (2018) 40

Dev, Pilaftsis, Yang, 14; Alva, Han, Ruiz, 15




Qiang Li's talk



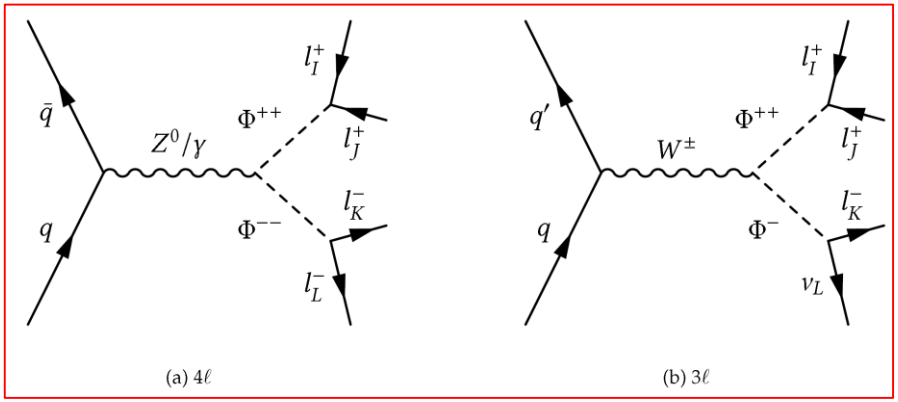

arXiv:1506.06020-ATLAS

# A: Collider Tests of Low-Scale Seesaw Models

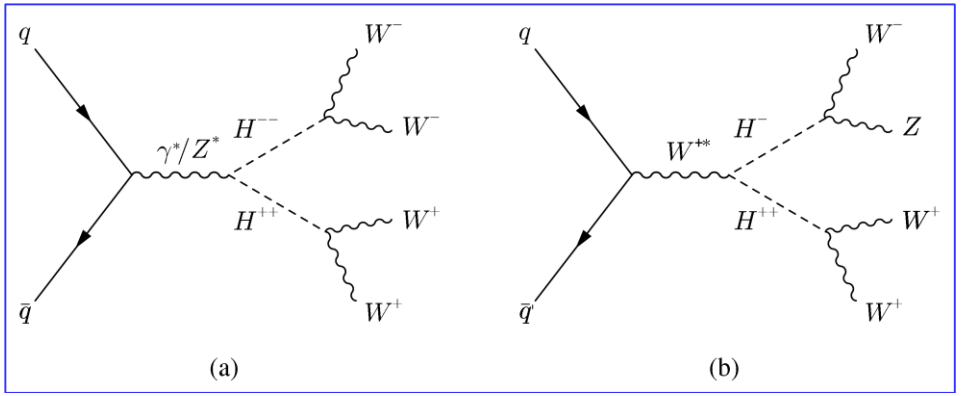


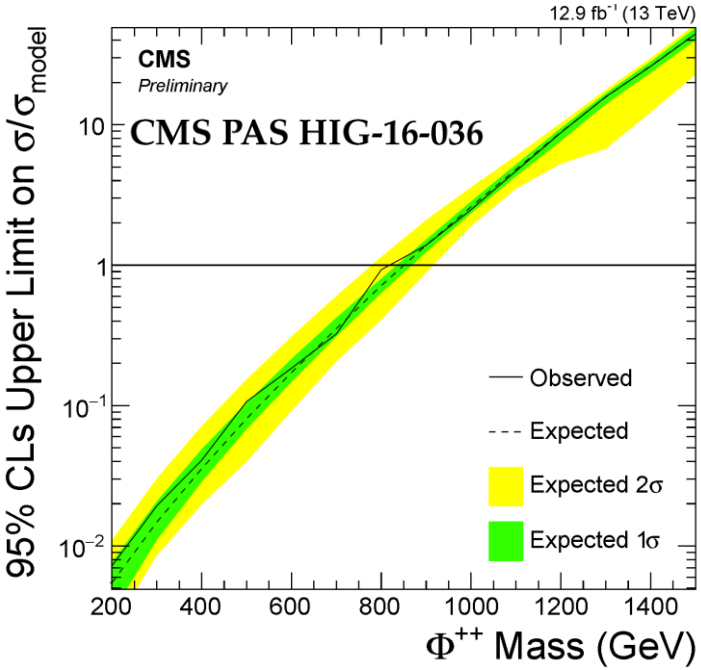
- **Experimental searches for the singly/doubly charged scalars from type-II seesaw**

**Leptonic Channel**

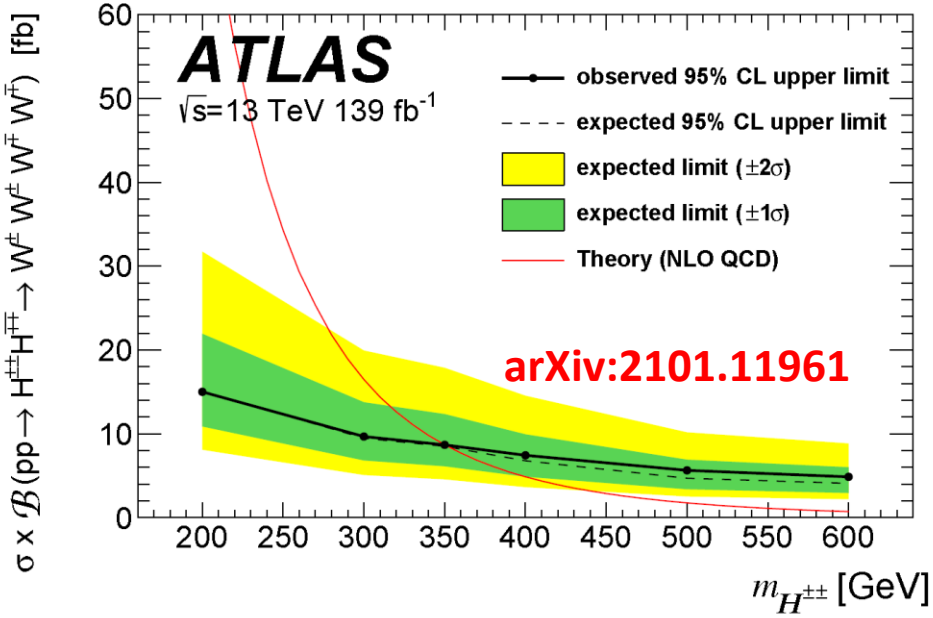



**Bosonic Channel**




(b) 100% $\mu\mu$

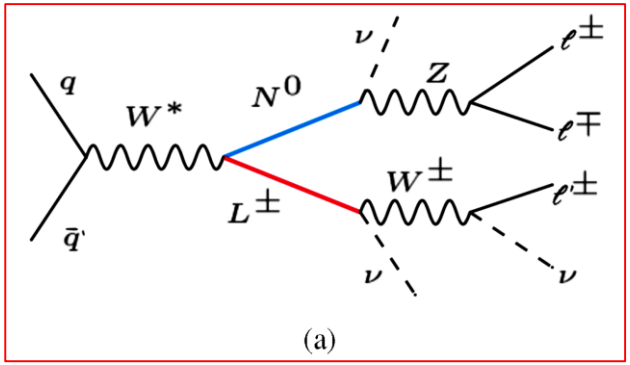


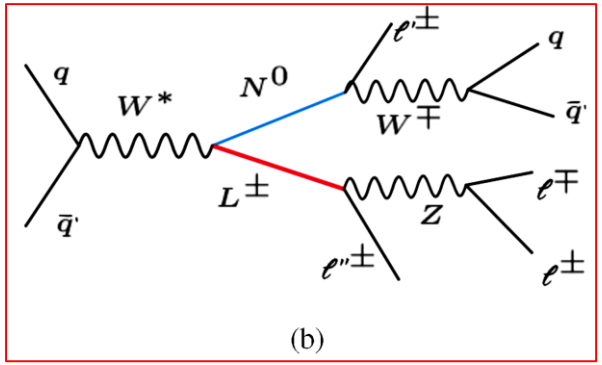

- **Depending on branching ratios: M > 800 GeV (leptonic) / 350 GeV (bosonic) at the 95% C.L.**

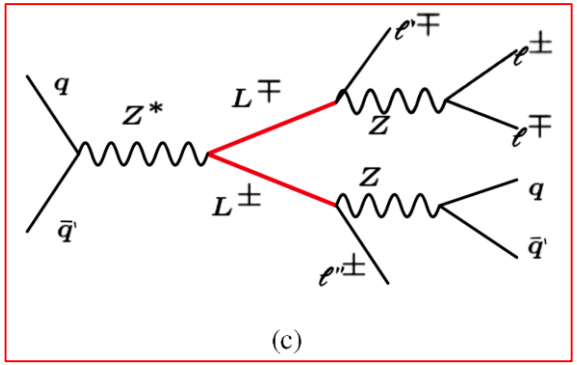
# A: Collider Tests of Low-Scale Seesaw Models

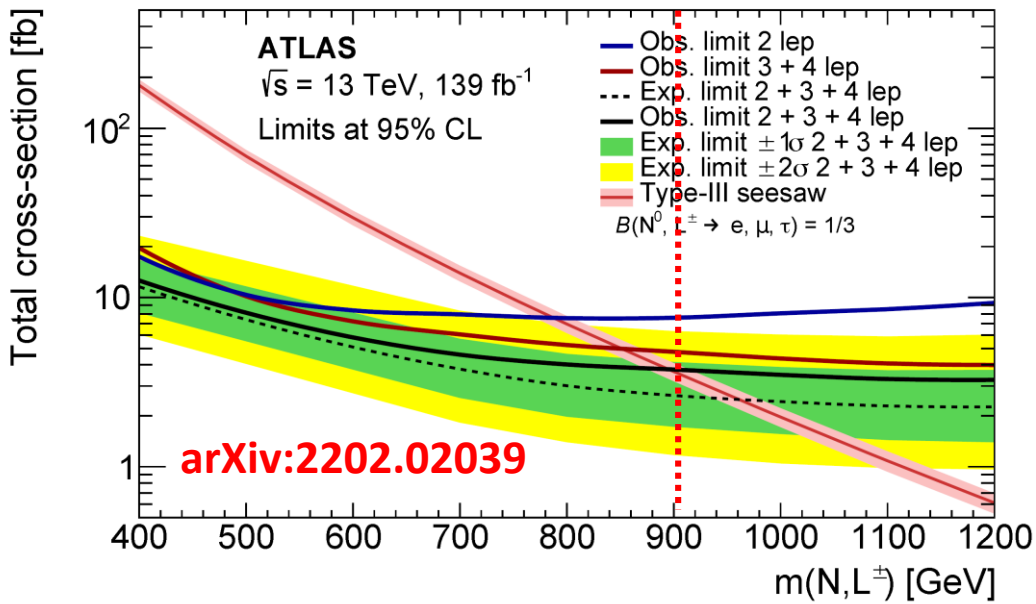


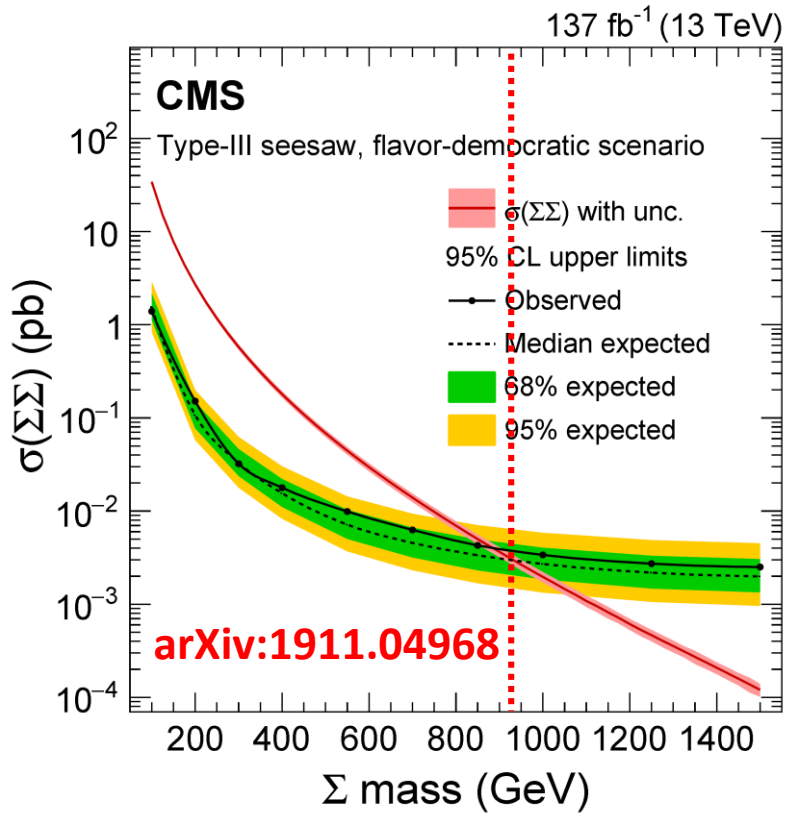
- **Experimental searches for neutral/charged heavy leptons from type-III seesaw**



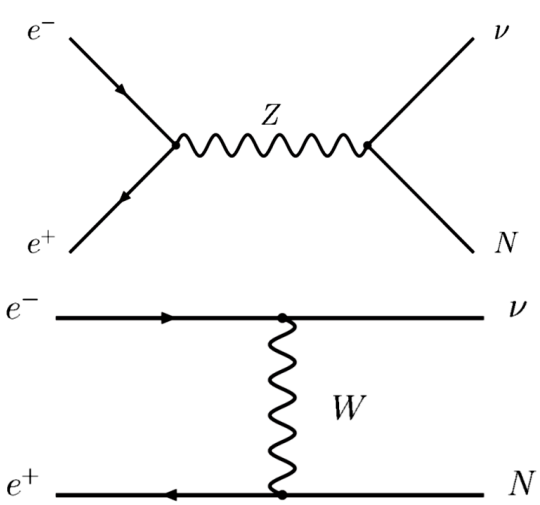



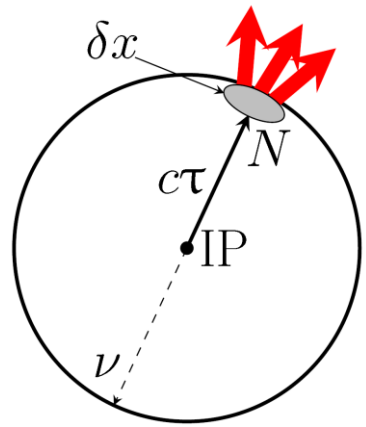

- **Constraints on the masses of neutral/charged heavy leptons: M > 910 GeV at the 95% C.L.**

# A: Collider Tests of Low-Scale Seesaw Models

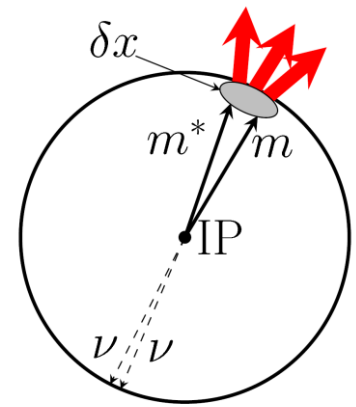


- **Displaced vertices as signals for heavy particles from seesaw models**




signal



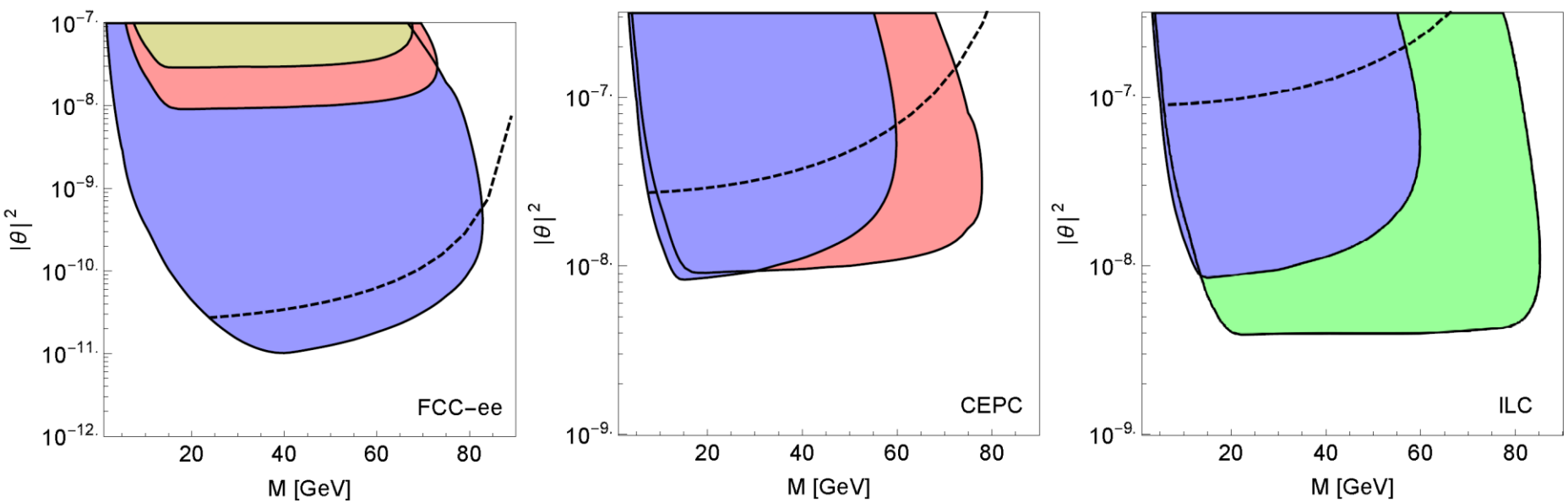

background

**Antusch et al., 16**

$$\theta_\alpha = \frac{y^*_{\nu_\alpha}}{\sqrt{2}} \frac{v_{\rm EW}}{M}$$

$$|\theta|^2 := \sum_\alpha |\theta_\alpha|^2$$

**Dev, Zhang, 18; Antusch et al., 18**




$E_{cm} = m_Z$; $E_{cm} = 250$ GeV; $E_{cm} = 350$ GeV; $E_{cm} = 500$ GeV; Conventional search (95% C.L.)

# Baryon- and Lepton-Nonconserving Processes

Weinberg, 79

Steven Weinberg
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(Received 13 August 1979)

A number of properties of possible baryon- and lepton-nonconserving processes are shown to follow under very general assumptions. Attention is drawn to the importance of measuring $\mu^+$ polarizations and $\bar{\nu}_e/e^+$ ratios in nucleon decay as a means of discriminating among specific models.

The sort of analysis used here in treating baryon nonconservation can also be applied to lepton nonconservation. A great difference is that there is a possible lepton-nonconserving term in the effective Lagrangian with dimensionality $d=5$:

$$f_{abmn}\bar{l}^C_{iaL}\, l_{jbL}\varphi_k^{(m)}\varphi_l^{(n)}\epsilon_{ik}\epsilon_{jl} + f_{abmn}'\bar{l}^C_{iaL}\, l_{jbL}\varphi_k^{(m)}\varphi_l^{(n)}\epsilon_{ij}\epsilon_{kl}\,, \qquad (20)$$

where $\varphi^{(m)}$ are one or more scalar doublets. We expect $f$ and $f'$ to be roughly of order $1/M$; one-loop graphs would give values of order $\alpha^2/M$.[13] The interaction (20) would produce a neutrino mass $m_\nu \simeq G_F^{-1} f$, or roughly $10^{-5}$ to $10^{-1}$ eV. This is well below any existing laboratory or cosmological limits, but there is no reason why this neutrino-mass matrix should be diagonal, and masses of this order might perhaps be observable in neutrino oscillation experiments.

**Unique dim-5 Weinberg operator for Majorana neutrino masses**

## SM Effective Field Theory (SMEFT)

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \sum_d \mathcal{L}^{(d)} = \mathcal{L}_{\rm SM} + \sum_{i=1}^{n_d} \frac{1}{\Lambda^{d-4}} C_i^{(d)} \mathcal{O}_i^{(d)}$$

| $X^3$ | | $\varphi^6$ and $\varphi^4 D^2$ | | $\psi^2\varphi^3$ | |
|---|---|---|---|---|---|
| $Q_G$ | $f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_\varphi$ | $(\varphi^\dagger\varphi)^3$ | $Q_{e\varphi}$ | $(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$ |
| $Q_{\widetilde G}$ | $f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$ | $Q_{\varphi\Box}$ | $(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$ | $Q_{u\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$ |
| $Q_W$ | $\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | $Q_{\varphi D}$ | $\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$ | $Q_{d\varphi}$ | $(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$ |
| $Q_{\widetilde W}$ | $\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$ | | | | |
| $X^2\varphi^2$ | | $\psi^2 X\varphi$ | | $\psi^2\varphi^2 D$ | |
| $Q_{\varphi G}$ | $\varphi^\dagger\varphi\, G^A_{\mu\nu} G^{A\mu\nu}$ | $Q_{eW}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\tau^I \varphi W^I_{\mu\nu}$ | $Q_{\varphi l}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$ |
| $Q_{\varphi\widetilde G}$ | $\varphi^\dagger\varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$ | $Q_{eB}$ | $(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$ | $Q_{\varphi l}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$ |
| $Q_{\varphi W}$ | $\varphi^\dagger\varphi\, W^I_{\mu\nu} W^{I\mu\nu}$ | $Q_{uG}$ | $(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G^A_{\mu\nu}$ | $Q_{\varphi e}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$ |
| $Q_{\varphi\widetilde W}$ | $\varphi^\dagger\varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$ | $Q_{uW}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\tau^I \widetilde\varphi\, W^I_{\mu\nu}$ | $Q_{\varphi q}^{(1)}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$ |
| $Q_{\varphi B}$ | $\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$ | $Q_{uB}$ | $(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$ | $Q_{\varphi q}^{(3)}$ | $(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$ |
| $Q_{\varphi\widetilde B}$ | $\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$ | $Q_{dG}$ | $(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G^A_{\mu\nu}$ | $Q_{\varphi u}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$ |
| $Q_{\varphi WB}$ | $\varphi^\dagger\tau^I\varphi\, W^I_{\mu\nu} B^{\mu\nu}$ | $Q_{dW}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\tau^I \varphi\, W^I_{\mu\nu}$ | $Q_{\varphi d}$ | $(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$ |
| $Q_{\varphi\widetilde WB}$ | $\varphi^\dagger\tau^I\varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$ | $Q_{dB}$ | $(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$ | $Q_{\varphi ud}$ | $i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$ |

Table 2: Dimension-six operators other than the four-fermion ones.

| $(\bar LL)(\bar LL)$ | | $(\bar RR)(\bar RR)$ | | $(\bar LL)(\bar RR)$ | |
|---|---|---|---|---|---|
| $Q_{ll}$ | $(\bar l_p \gamma_\mu l_r)(\bar l_s \gamma^\mu l_t)$ | $Q_{ee}$ | $(\bar e_p \gamma_\mu e_r)(\bar e_s \gamma^\mu e_t)$ | $Q_{le}$ | $(\bar l_p \gamma_\mu l_r)(\bar e_s \gamma^\mu e_t)$ |
| $Q_{qq}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar q_s \gamma^\mu q_t)$ | $Q_{uu}$ | $(\bar u_p \gamma_\mu u_r)(\bar u_s \gamma^\mu u_t)$ | $Q_{lu}$ | $(\bar l_p \gamma_\mu l_r)(\bar u_s \gamma^\mu u_t)$ |
| $Q_{qq}^{(3)}$ | $(\bar q_p \gamma_\mu \tau^I q_r)(\bar q_s \gamma^\mu \tau^I q_t)$ | $Q_{dd}$ | $(\bar d_p \gamma_\mu d_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{ld}$ | $(\bar l_p \gamma_\mu l_r)(\bar d_s \gamma^\mu d_t)$ |
| $Q_{lq}^{(1)}$ | $(\bar l_p \gamma_\mu l_r)(\bar q_s \gamma^\mu q_t)$ | $Q_{eu}$ | $(\bar e_p \gamma_\mu e_r)(\bar u_s \gamma^\mu u_t)$ | $Q_{qe}$ | $(\bar q_p \gamma_\mu q_r)(\bar e_s \gamma^\mu e_t)$ |
| $Q_{lq}^{(3)}$ | $(\bar l_p \gamma_\mu \tau^I l_r)(\bar q_s \gamma^\mu \tau^I q_t)$ | $Q_{ed}$ | $(\bar e_p \gamma_\mu e_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{qu}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar u_s \gamma^\mu u_t)$ |
| | | $Q_{ud}^{(1)}$ | $(\bar u_p \gamma_\mu u_r)(\bar d_s \gamma^\mu d_t)$ | $Q_{qu}^{(8)}$ | $(\bar q_p \gamma_\mu T^A q_r)(\bar u_s \gamma^\mu T^A u_t)$ |
| | | $Q_{ud}^{(8)}$ | $(\bar u_p \gamma_\mu T^A u_r)(\bar d_s \gamma^\mu T^A d_t)$ | $Q_{qd}^{(1)}$ | $(\bar q_p \gamma_\mu q_r)(\bar d_s \gamma^\mu d_t)$ |
| | | | | $Q_{qd}^{(8)}$ | $(\bar q_p \gamma_\mu T^A q_r)(\bar d_s \gamma^\mu T^A d_t)$ |
| $(\bar LR)(\bar RL)$ and $(\bar LR)(\bar LR)$ | | $B$-violating | | | |
| $Q_{ledq}$ | $(\bar l_p^j e_r)(\bar d_s q_t^j)$ | $Q_{duq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$ | | |
| $Q_{quqd}^{(1)}$ | $(\bar q_p^j u_r)\varepsilon_{jk}(\bar q_s^k d_t)$ | $Q_{qqu}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$ | | |
| $Q_{quqd}^{(8)}$ | $(\bar q_p^j T^A u_r)\varepsilon_{jk}(\bar q_s^k T^A d_t)$ | $Q_{qqq}$ | $\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$ | | |
| $Q_{lequ}^{(1)}$ | $(\bar l_p^j e_r)\varepsilon_{jk}(\bar q_s^k u_t)$ | $Q_{duu}$ | $\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$ | | |
| $Q_{lequ}^{(3)}$ | $(\bar l_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar q_s^k \sigma^{\mu\nu} u_t)$ | | | | |

Table 3: Four-fermion operators.

**Buchmüller & Wyler, 86**

**Brivio & Trott, Phys. Rept. 793 (2019) 1**

**Dim-6 operators in the Warsaw basis**

# Dimension-Six Terms in the Standard Model Lagrangian

Here we perform their classification once again from the outset. Assuming baryon number conservation, we find $15 + 19 + 25 = 59$ independent operators (barring flavour structure and Hermitian conjugations), as compared to $16 + 35 + 29 = 80$ in Ref. [3]. The three summed numbers refer to operators containing 0, 2 and 4 fermion fields. If the assumption of baryon number conservation is relaxed, 4 new operators arise in the four-fermion sector.

**Grzadkowski, Iskrzynski, Misiak, Rosiek, 1008.4884**

**Jiang-Hao Yu's talk**

# B: Approach of Effective Field Theories



- **The type-I seesaw model as a UV-complete theory**

$$\mathcal{L}_{\rm UV} = \mathcal{L}_{\rm SM} + \overline{N_{\rm R}} {\rm i}\partial\!\!\!/ N_{\rm R} - \left( \frac{1}{2} \overline{N_{\rm R}^c} M N_{\rm R} + \overline{\ell_{\rm L}} Y_\nu \widetilde{H} N_{\rm R} + {\rm h.c.} \right)$$

- **Tree-level matching: simply applying the EOM**

$$\left( {\rm i}\partial\!\!\!/ - M \right) N - \left( Y_\nu^\dagger \widetilde{H}^\dagger \ell_{\rm L} + Y_\nu^{\rm T} \widetilde{H}^{\rm T} \ell_{\rm L}^c \right) = 0$$

- **Expansion up to $M^{-2}$ (dim-6 operators)**

$$N \simeq - \left( M^{-1} + M^{-2} {\rm i}\partial\!\!\!/ \right) \left( Y_\nu^\dagger \widetilde{H}^\dagger \ell_{\rm L} + Y_\nu^{\rm T} \widetilde{H}^{\rm T} \ell_{\rm L}^c \right)$$

- **Seesaw Effective Field Theory (SEFT) @ tree level**

$$\mathcal{L}_{\rm SEFT}^{\rm tree} = \mathcal{L}_{\rm SM} + \left[ \frac{1}{2} C_{\alpha\beta}^{(5)} \mathcal{O}_{\alpha\beta}^{(5)} + {\rm h.c.} \right] + C_{\alpha\beta}^{(6)} \mathcal{O}_{\alpha\beta}^{(6)}$$

$$\mathcal{O}_{\alpha\beta}^{(5)} = \overline{\ell_{\alpha{\rm L}}} \widetilde{H} \widetilde{H}^{\rm T} \ell_{\beta{\rm L}}^c$$

$$C_{\alpha\beta}^{(5)} = \left( Y_\nu M^{-1} Y_\nu^{\rm T} \right)_{\alpha\beta}$$

**Neutrino masses & flavor mixing**

$$\mathcal{O}_{\alpha\beta}^{(6)} = \left( \overline{\ell_{\alpha{\rm L}}} \widetilde{H} \right) {\rm i}\partial\!\!\!/ \left( \widetilde{H}^\dagger \ell_{\beta{\rm L}} \right)$$

$$C_{\alpha\beta}^{(6)} = \left( Y_\nu M^{-2} Y_\nu^\dagger \right)_{\alpha\beta}$$

**Unitarity violation of flavor mixing matrix**

## After the spontaneous gauge symmetry breaking

$$\mathcal{L}_{\rm SEFT} = \overline{\nu_{\alpha\rm L}}\left(\mathbf{1} + M_{\rm D}M^{-2}M_{\rm D}^{\dagger}\right)_{\alpha\beta} {\rm i}\partial\!\!\!/\nu_{\beta\rm L} - \left[\overline{l_{\alpha\rm L}}\,(M_l)_{\alpha\beta}\,l_{\beta\rm R} + \frac{1}{2}\overline{\nu_{\alpha\rm L}}\,(M_\nu)_{\alpha\beta}\,\nu^{\rm c}_{\beta\rm L} + {\rm h.c.}\right]$$
$$+\left(\frac{g_2}{\sqrt{2}}\overline{l_{\alpha\rm L}}\gamma^\mu\nu_{\alpha\rm L}W^-_\mu + {\rm h.c.}\right) + \frac{g_2}{2\cos\theta_{\rm w}}\overline{\nu_{\alpha\rm L}}\gamma^\mu\nu_{\alpha\rm L}Z_\mu$$

**Normalization:** $\nu_{\rm L} \to V\nu_{\rm L}$ with $V = \mathbf{1} - RR^\dagger/2$ and $R \equiv M_{\rm D}M^{-1}$

**Diagonalization:** $U_0^\dagger V M_\nu V^T U_0^* = \widehat{M}_\nu = {\rm Diag}\{m_1, m_2, m_3\}$

## The SEFT Lagrangian in the mass basis:

$$\boxed{U = VU_0}$$

$$\mathcal{L}_{\rm SEFT} = \overline{\nu_{\rm L}}{\rm i}\partial\!\!\!/\nu_{\rm L} - \left(\overline{l_{\rm L}}M_l l_{\rm R} + \frac{1}{2}\overline{\nu_{\rm L}}\widehat{M}_\nu\nu^{\rm c}_{\rm L} + {\rm h.c.}\right) + \left(\frac{g_2}{\sqrt{2}}\overline{l_{\rm L}}\gamma^\mu \boxed{U}\nu_{\rm L}W^-_\mu + {\rm h.c.}\right)$$
$$+\frac{g_2}{2\cos\theta_{\rm w}}\overline{\nu_{\rm L}}\gamma^\mu \boxed{U^\dagger U}\nu_{\rm L}Z_\mu$$

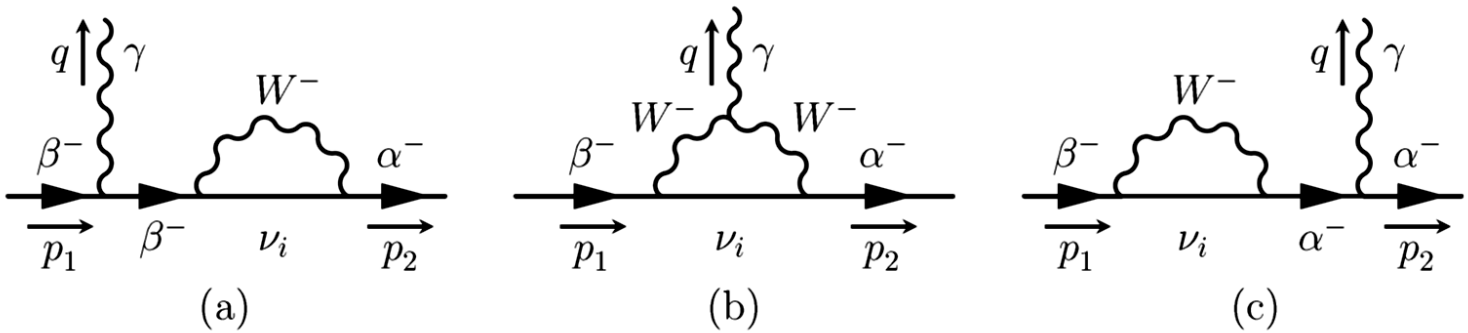
Non-unitary flavor mixing

Non-unitarity

**Minimal unitarity violation (MUV) "equivalent" to SEFT @ tree level**

Antusch et al., hep-ph/0607020; Antusch & Fischer, 1407.6607

## LFV decays of charged leptons in the MUV scheme




**The decay width**

Xing & Zhang, 2009.09717

$$\Gamma\left(\beta^- \to \alpha^- + \gamma\right) \simeq \frac{\alpha_{\rm em} G_{\rm F}^2 m_\beta^5}{128\pi^4} \left| \sum_{i=1}^{3} U_{\alpha i} U_{\beta i}^* \left( -\frac{5}{6} + \frac{m_i^2}{4M_W^2} \right) \right|^2$$

**However, the calculation in the full theory for $M_i >> M_W$ gives**

$$\Gamma\left(\beta^- \to \alpha^- + \gamma\right) \simeq \frac{\alpha_{\rm em} G_{\rm F}^2 m_\beta^5}{128\pi^4} \left| \sum_{i=1}^{3} U_{\alpha i} U_{\beta i}^* \left( -\frac{5}{6} + \frac{m_i^2}{4M_W^2} \right) \boxed{-\frac{1}{3}\left(RR^\dagger\right)_{\alpha\beta}} \right|^2$$

$$\mathcal{B}\left(\mu^- \to e^- + \gamma\right) < 4.2 \times 10^{-13}$$
$$\mathcal{B}\left(\tau^- \to e^- + \gamma\right) < 3.3 \times 10^{-8}$$
$$\mathcal{B}\left(\tau^- \to \mu^- + \gamma\right) < 4.4 \times 10^{-8}$$

**Question: What goes wrong with tree-level SEFT? EFT must give the same result as UV theory for low-energy observables**

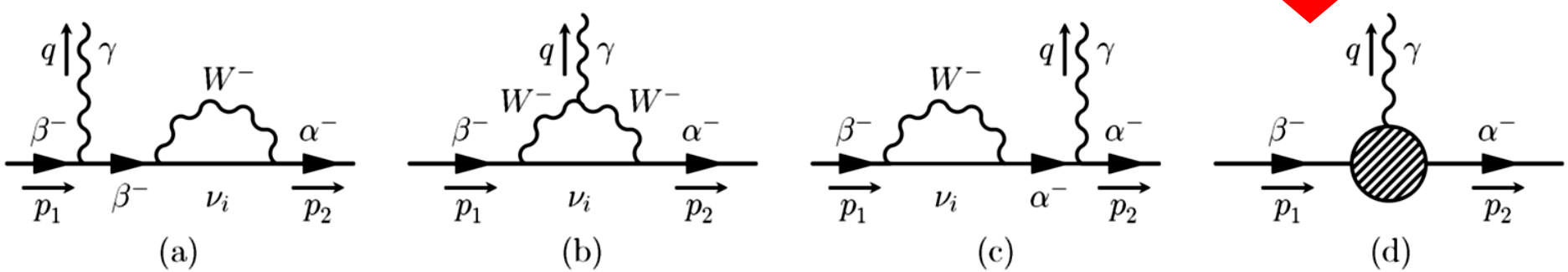
**Answer:** **Radiative decays at one-loop require one-loop matching!**

**Another two relevant dim-6 operators @ one loop** Zhang & S.Z., 2102.04954

$$\mathcal{L}^{(6)}_{\rm loop} = \frac{\left(Y_\nu M^{-2} Y_\nu^\dagger Y_l\right)_{\alpha\beta}}{24\,(4\pi)^2}\left[g_1\left(\overline{\ell_{\alpha\rm L}}\sigma_{\mu\nu}E_{\beta\rm R}\right)HB^{\mu\nu} + 5g_2\left(\overline{\ell_{\alpha\rm L}}\sigma_{\mu\nu}E_{\beta\rm R}\right)\tau^I HW^{I\mu\nu}\right] + \text{h.c.}$$

**leading to the direct EM-dipole vertex**

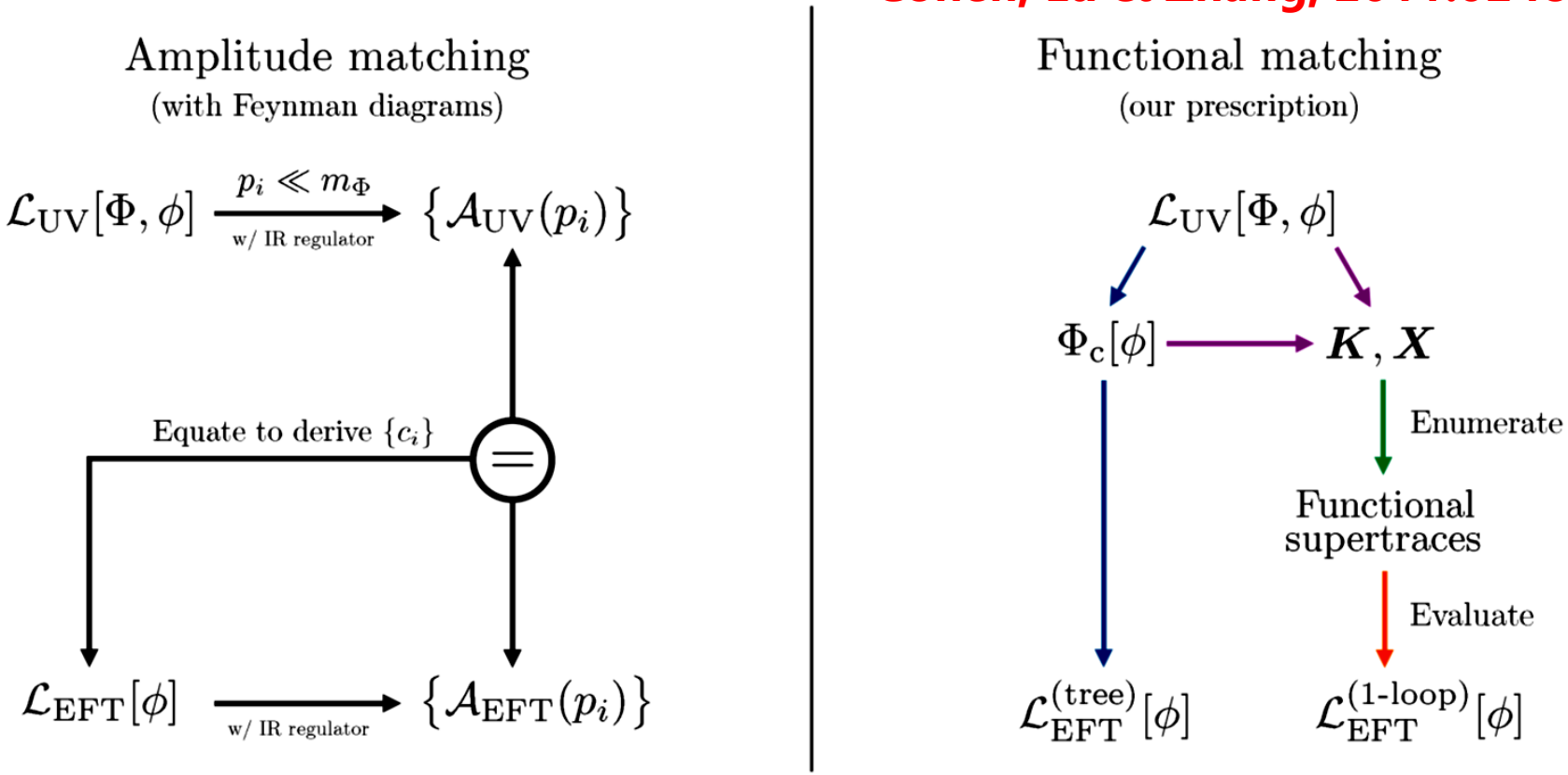
$$\mathcal{L}_{\rm SEFT} = \overline{\nu_{\rm L}}{\rm i}\partial\!\!\!/\nu_{\rm L} - \left(\overline{l_{\rm L}}M_l l_{\rm R} + \frac{1}{2}\overline{\nu_{\rm L}}\widehat{M}_\nu \nu^{\rm c}_{\rm L} + \text{h.c.}\right) + \left(\frac{g_2}{\sqrt{2}}\overline{l_{\rm L}}\gamma^\mu U\nu_{\rm L}W^-_\mu + \text{h.c.}\right)$$
$$+\frac{g_2}{2\cos\theta_{\rm w}}\overline{\nu_{\rm L}}\gamma^\mu U^\dagger U\nu_{\rm L}Z_\mu \boxed{-\frac{eg_2^2}{12\,(4\pi)^2\,M_W^2}\overline{l_{\rm L}}\sigma_{\mu\nu}RR^\dagger M_l l_{\rm R}F^{\mu\nu}} + \text{h.c.}\ ,$$




**exactly reproducing the result in the full theory (with $M_i >> M_W$)**

## Matching between UV theory and EFT

Cohen, Lu & Zhang, 2011.02484




- **Functional method for one-loop matching**
- **Covariant Derivative Expansion (CDE)** Gaillard, 86; Chen, 86; Cheyette, 88
- **Expansion by Regions (hard and soft loop momentum)** Beneke & Smirnov, 98; Smirnov, 02

# B: Approach of Effective Field Theories



| $X^2H^2$ | |
|---|---|
| $\mathcal{O}_{HB}$ | $B_{\mu\nu}B^{\mu\nu}H^\dagger H$ |
| $\mathcal{O}_{HW}$ | $W^I_{\mu\nu}W^{I\mu\nu}H^\dagger H$ |
| $\mathcal{O}_{HWB}$ | $W^I_{\mu\nu}B^{\mu\nu}\left(H^\dagger\tau^I H\right)$ |
| $H^4D^2$ | |
| $\mathcal{O}_{H\Box}$ | $\left(H^\dagger H\right)\Box\left(H^\dagger H\right)$ |
| $\mathcal{O}_{HD}$ | $\left(H^\dagger D_\mu H\right)^*\left(H^\dagger D^\mu H\right)$ |
| $H^6$ | |
| $\mathcal{O}_H$ | $\left(H^\dagger H\right)^3$ |
| $\psi^2XH$ | |
| $\mathcal{O}^{\alpha\beta}_{eB}$ | $\left(\overline{\ell_{\alpha\mathrm{L}}}\sigma^{\mu\nu}E_{\beta\mathrm{R}}\right)HB_{\mu\nu}$ |
| $\mathcal{O}^{\alpha\beta}_{eW}$ | $\left(\overline{\ell_{\alpha\mathrm{L}}}\sigma^{\mu\nu}E_{\beta\mathrm{R}}\right)\tau^I HW^I_{\mu\nu}$ |

| $\psi^2DH^2$ | |
|---|---|
| $\mathcal{O}^{(1)\alpha\beta}_{HQ}$ | $\left(\overline{Q_{\alpha\mathrm{L}}}\gamma^\mu Q_{\beta\mathrm{L}}\right)\left(H^\dagger \mathrm{i}\overleftrightarrow{D}_\mu H\right)$ |
| $\mathcal{O}^{(3)\alpha\beta}_{HQ}$ | $\left(\overline{Q_{\alpha\mathrm{L}}}\gamma^\mu\tau^I Q_{\beta\mathrm{L}}\right)\left(H^\dagger \mathrm{i}\overleftrightarrow{D}^I_\mu H\right)$ |
| $\mathcal{O}^{\alpha\beta}_{HU}$ | $\left(\overline{U_{\alpha\mathrm{R}}}\gamma^\mu U_{\beta\mathrm{R}}\right)\left(H^\dagger \mathrm{i}\overleftrightarrow{D}_\mu H\right)$ |
| $\mathcal{O}^{\alpha\beta}_{Hd}$ | $\left(\overline{D_{\alpha\mathrm{R}}}\gamma^\mu D_{\beta\mathrm{R}}\right)\left(H^\dagger \mathrm{i}\overleftrightarrow{D}_\mu H\right)$ |
| $\mathcal{O}^{(1)\alpha\beta}_{H\ell}$ | $\left(\overline{\ell_{\alpha\mathrm{L}}}\gamma^\mu \ell_{\beta\mathrm{L}}\right)\left(H^\dagger \mathrm{i}\overleftrightarrow{D}_\mu H\right)$ |
| $\mathcal{O}^{(3)\alpha\beta}_{H\ell}$ | $\left(\overline{\ell_{\alpha\mathrm{L}}}\gamma^\mu\tau^I \ell_{\beta\mathrm{L}}\right)\left(H^\dagger \mathrm{i}\overleftrightarrow{D}^I_\mu H\right)$ |
| $\mathcal{O}^{\alpha\beta}_{He}$ | $\left(\overline{E_{\alpha\mathrm{R}}}\gamma^\mu E_{\beta\mathrm{R}}\right)\left(H^\dagger \mathrm{i}\overleftrightarrow{D}_\mu H\right)$ |
| $\psi^2H^3$ | |
| $\mathcal{O}^{\alpha\beta}_{UH}$ | $\left(\overline{Q_{\alpha\mathrm{L}}}\widetilde{H}U_{\beta\mathrm{R}}\right)\left(H^\dagger H\right)$ |
| $\mathcal{O}^{\alpha\beta}_{dH}$ | $\left(\overline{Q_{\alpha\mathrm{L}}}HD_{\beta\mathrm{R}}\right)\left(H^\dagger H\right)$ |
| $\mathcal{O}^{\alpha\beta}_{eH}$ | $\left(\overline{\ell_{\alpha\mathrm{L}}}HE_{\beta\mathrm{R}}\right)\left(H^\dagger H\right)$ |

| Four-quark | |
|---|---|
| $\mathcal{O}^{(1)\alpha\beta\gamma\lambda}_{QU}$ | $\left(\overline{Q_{\alpha\mathrm{L}}}\gamma^\mu Q_{\beta\mathrm{L}}\right)\left(\overline{U_{\gamma\mathrm{R}}}\gamma_\mu U_{\lambda\mathrm{R}}\right)$ |
| $\mathcal{O}^{(8)\alpha\beta\gamma\lambda}_{QU}$ | $\left(\overline{Q_{\alpha\mathrm{L}}}\gamma^\mu T^A Q_{\beta\mathrm{L}}\right)\left(\overline{U_{\gamma\mathrm{R}}}\gamma_\mu T^A U_{\lambda\mathrm{R}}\right)$ |
| $\mathcal{O}^{(1)\alpha\beta\gamma\lambda}_{Qd}$ | $\left(\overline{Q_{\alpha\mathrm{L}}}\gamma^\mu Q_{\beta\mathrm{L}}\right)\left(\overline{D_{\gamma\mathrm{R}}}\gamma_\mu D_{\lambda\mathrm{R}}\right)$ |
| $\mathcal{O}^{(8)\alpha\beta\gamma\lambda}_{Qd}$ | $\left(\overline{Q_{\alpha\mathrm{L}}}\gamma^\mu T^A Q_{\beta\mathrm{L}}\right)\left(\overline{D_{\gamma\mathrm{R}}}\gamma_\mu T^A D_{\lambda\mathrm{R}}\right)$ |
| $\mathcal{O}^{(1)\alpha\beta\gamma\lambda}_{QUQd}$ | $\left(\overline{Q^a_{\alpha\mathrm{L}}}U_{\beta\mathrm{R}}\right)\epsilon^{ab}\left(\overline{Q^b_{\gamma\mathrm{L}}}D_{\lambda\mathrm{R}}\right)$ |
| Four-lepton | |
| $\mathcal{O}^{\alpha\beta\gamma\beta}_{\ell\ell}$ | $\left(\overline{\ell_{\alpha\mathrm{L}}}\gamma^\mu \ell_{\beta\mathrm{L}}\right)\left(\overline{\ell_{\gamma\mathrm{L}}}\gamma_\mu \ell_{\lambda\mathrm{L}}\right)$ |
| $\mathcal{O}^{\alpha\beta\gamma\lambda}_{\ell e}$ | $\left(\overline{\ell_{\alpha\mathrm{L}}}\gamma^\mu \ell_{\beta\mathrm{L}}\right)\left(\overline{E_{\gamma\mathrm{R}}}\gamma_\mu E_{\lambda\mathrm{R}}\right)$ |

Zhang & S.Z., 2107.12133

| Semi-leptonic | | | | | |
|---|---|---|---|---|---|
| $\mathcal{O}^{(1)\alpha\beta\gamma\lambda}_{\ell Q}$ | $\left(\overline{\ell_{\alpha\mathrm{L}}}\gamma^\mu \ell_{\beta\mathrm{L}}\right)\left(\overline{Q_{\gamma\mathrm{L}}}\gamma_\mu Q_{\lambda\mathrm{L}}\right)$ | $\mathcal{O}^{\alpha\beta\gamma\lambda}_{\ell U}$ | $\left(\overline{\ell_{\alpha\mathrm{L}}}\gamma^\mu \ell_{\beta\mathrm{L}}\right)\left(\overline{U_{\gamma\mathrm{R}}}\gamma_\mu U_{\lambda\mathrm{R}}\right)$ | $\mathcal{O}^{\alpha\beta\gamma\lambda}_{\ell edQ}$ | $\left(\overline{\ell_{\alpha\mathrm{L}}}E_{\beta\mathrm{R}}\right)\left(\overline{D_{\gamma\mathrm{R}}}Q_{\lambda\mathrm{L}}\right)$ |
| $\mathcal{O}^{(3)\alpha\beta\gamma\lambda}_{\ell Q}$ | $\left(\overline{\ell_{\alpha\mathrm{L}}}\gamma^\mu\tau^I \ell_{\beta\mathrm{L}}\right)\left(\overline{Q_{\gamma\mathrm{L}}}\gamma_\mu\tau^I Q_{\lambda\mathrm{L}}\right)$ | $\mathcal{O}^{\alpha\beta\gamma\lambda}_{\ell d}$ | $\left(\overline{\ell_{\alpha\mathrm{L}}}\gamma^\mu \ell_{\beta\mathrm{L}}\right)\left(D_{\gamma\mathrm{R}}\gamma_\mu D_{\lambda\mathrm{R}}\right)$ | $\mathcal{O}^{(1)\alpha\beta\gamma\lambda}_{\ell eQU}$ | $\left(\overline{\ell^a_{\alpha\mathrm{L}}}E_{\beta\mathrm{R}}\right)\epsilon^{ab}\left(\overline{Q^b_{\gamma\mathrm{L}}}U_{\lambda\mathrm{R}}\right)$ |

**Out of 59 operators in the Warsaw basis, 31 dim-6 operators in SEFT**

# B: Approach of Effective Field Theories



- EFTs as a useful & powerful tool to probe new physics beyond the SM
- SEFT@1-loop necessary for precision tests of neutrino mass models

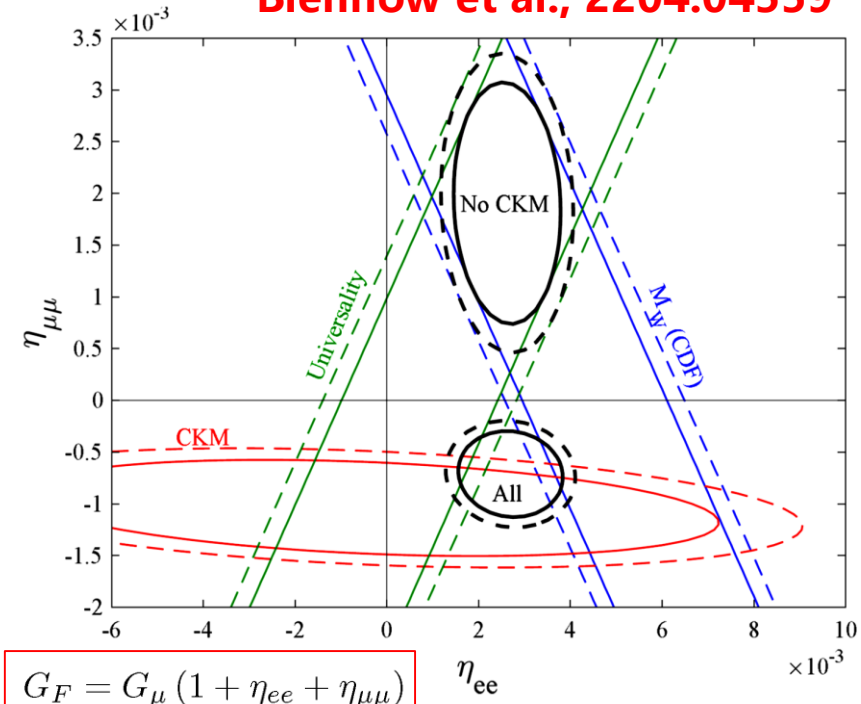
Zhang & S.Z., 2107.12133 Du, Li & Yu, 2201.04646 Liao & Ma, 2210.04270

Coy & Frigerio, 2110.09126 Li, Zhang & S.Z., 2201.05082

Ohlsson & Penrow, 2201.00840 Seesaw models, Zee model, Scotogenic model

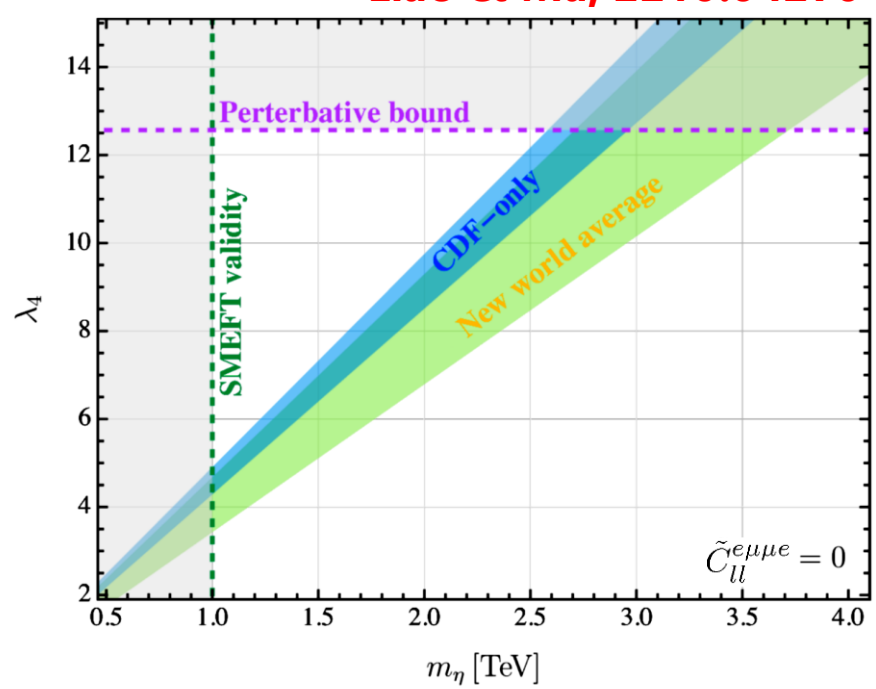
Neutrino mass connection to the W-mass anomaly: Cheng et al., 2208.06760

Blennow et al., 2204.04559




$$G_F = G_\mu \left(1 + \eta_{ee} + \eta_{\mu\mu}\right)$$

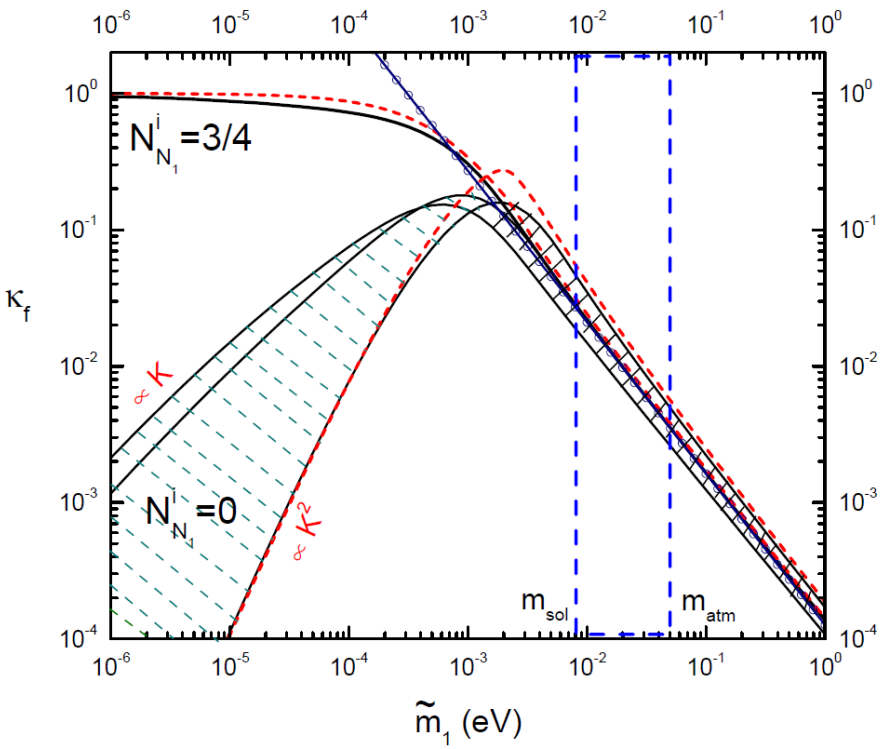
Liao & Ma, 2210.04270



- **More observables for the seesaw model of neutrino masses and baryon asymmetry in the Universe (BAU)**

Cui & Xianyu, PRL, 22

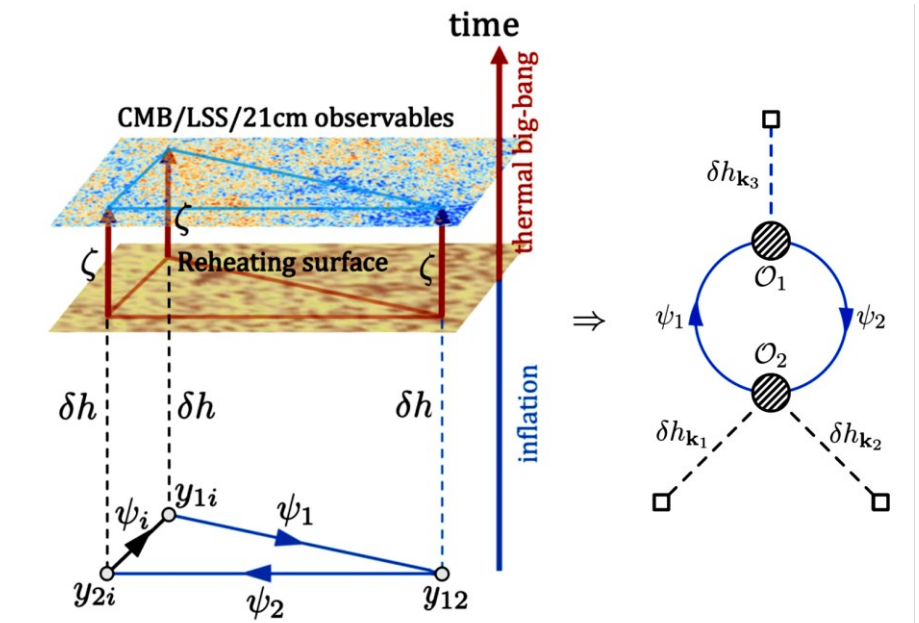
$$\eta_B \approx -0.96 \times 10^{-2} \kappa_f \varepsilon_1$$

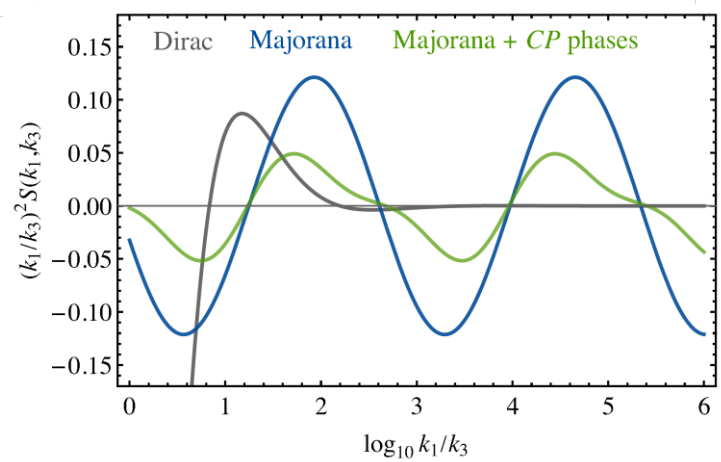



**LNV/CPV/Out-of-equilibrium decays of heavy Majorana neutrinos: leptogenesis for BAU**

Fukugita & Yanagida, 86; Buchmueller et al., 04

**Probing Leptogenesis with the Cosmological Collider**



# Summary

1. Origin of tiny neutrino masses calls for new physics beyond the Standard Model; Dirac or Majorana nature crucially important for model building

2. Depending on the mass scale of new physics, different approaches can be taken to move forward:

   (A) Direct searches; (B) Precision tests; (C) Cosmological observations

3. Other important aspects should be noticed: quark & lepton flavor mixing; connections to dark sectors; interplay with astronomy & cosmology; new ideas from atomic physics/condensed matter physics/…

**TeV Leptogenesis**

调研简报
---主要思路
---存在问题
---初步设想

TeV物理工作组第一次会议日程

郭万磊/张贺/周顺/邢志忠（高能所）

| 8月29日 下午 | |
|---|---|
| 会议报告 | 主持人：李学潜 教授 |
| 14:00-14:30 | 报告题目：Bounds on unparticles couplings to electrons<br>报告人： 廖 益 教授（南开大学） |
| 14:30-15:00 | 报告题目：Unparticle Physics phenomenology<br>报告人： 魏正涛 副教授（南开大学） |
| 15:00-15:20 | 报告题目：Some Phenomenologies about Unparticle Physics<br>报告人： 朱国怀 副教授（浙江大学） |
| 15:20-15:40 | 报告题目：Unparticle and supersymmetry physics<br>报告人： 张 昊 博士（北京大学） |
| 15:40-15:50 | 休息 |
| 会议报告 | 主持人：马建平 研究员 |
| 15:50-16:10 | 报告题目：Unnaturalness of Cancellation in the TeV Seesaw Models<br>报告人： 周 顺 博士（中科院高能所） |
| 16:10-16:40 | 报告题目：暗物质探测对超对称模型的限制<br>报告人： 毕效军 副研究员（中科院高能所） |
| 16:40—16:50 | 休息 |
| 会议报告 | 主持人：邝宇平 院士 |
| 16:50—18:10 | 讨论 |

2007 TeV 物理工作组会议日程
8月27日-8月30日 大连

**Thanks for your attention!**