Scalar and Tensor Neutrino Interactions

In collaboration with Tao Han, Jiajun Liao, and Danny Marfatia
[arXiv:2004.13869]

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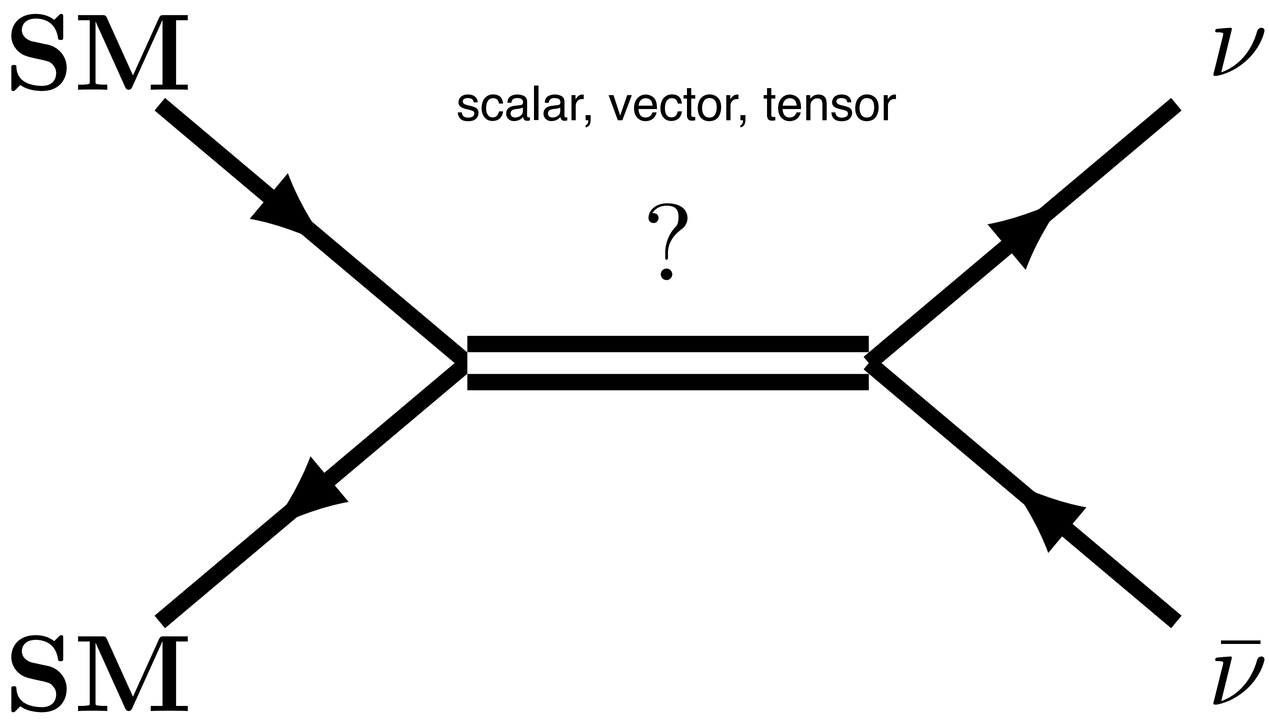
Motivation

- Neutrino oscillations call for new physics in the neutrino sector.
- The absence of BSM signals at the LHC indicates new physics scale may be beyond the kinematic reach.



SMEFT

- The most prominent EFT is the SMEFT, respecting the full SM gauge symmetries with only SM field contents
- Nonstandard neutrino interactions are related to the di-lepton interactions by the gauge symmetry at dimension-six level.
- Scalar- and tensor-like neutral current neutrino interactions are absent in SMEFT

SMNEFT = SMEFT + N

[arXiv:0806.0876]

SMNEFT

LEFT

[arXiv:1905.08699]

$(\overline{L}L)(\overline{L}L)$ and $(\overline{R}R)(\overline{R}R)$		$(\overline{L}L)(\overline{R}R)$		$(\overline{L}R)(\overline{R}L)$ and $(\overline{L}R)(\overline{L}R)$	
$\mathcal{O}_{ll}$	$(\bar{l}_\alpha\gamma_\mu l_\beta)(\bar{l}_\gamma\gamma^\mu l_\delta)$	$\mathcal{O}_{le}$	$(\bar{l}_\alpha\gamma_\mu l_\beta)(\bar{e}_\gamma\gamma^\mu e_\delta)$	$\mathcal{O}_{elqd}$	$(\bar{e}_\alpha l^j_\beta)(\bar{q}^j_\gamma d_\delta)$
$\mathcal{O}^{(1)}_{lq}$	$(\bar{l}_\alpha\gamma_\mu l_\beta)(\bar{q}_\gamma\gamma^\mu q_\delta)$	$\mathcal{O}_{lu}$	$(\bar{l}_\alpha\gamma_\mu l_\beta)(\bar{u}_\gamma\gamma^\mu u_\delta)$	$\mathcal{O}_{eluq}$	$(\bar{e}_\alpha l^j_\beta)\epsilon_{jk}(\bar{u}_\gamma q^k_\delta)$
$\mathcal{O}^{(3)}_{lq}$	$(\bar{l}_\alpha\gamma_\mu\tau^I l_\beta)(\bar{q}_\gamma\gamma^\mu\tau^I q_\delta)$	$\mathcal{O}_{ld}$	$(\bar{l}_\alpha\gamma_\mu l_\beta)(\bar{d}_\gamma\gamma^\mu d_\delta)$	$\mathcal{O}'_{eluq}$	$(\bar{e}_\alpha\sigma_{\mu\nu}l^j_\beta)\epsilon_{jk}(\bar{u}_\gamma\sigma^{\mu\nu}q^k_\delta)$
$\mathcal{O}_{Ne}$	$(\overline{N}_\alpha\gamma_\mu N_\beta)(\bar{e}_\gamma\gamma^\mu e_\delta)$	$\mathcal{O}_{Nl}$	$(\overline{N}_\alpha\gamma_\mu N_\beta)(\bar{l}_\gamma\gamma^\mu l_\delta)$	$\mathcal{O}_{Nlel}$	$(\overline{N}_\alpha l^j_\beta)\epsilon_{jk}(\bar{e}_\gamma l^k_\delta)$
$\mathcal{O}_{Nu}$	$(\overline{N}_\alpha\gamma_\mu N_\beta)(\bar{u}_\gamma\gamma^\mu u_\delta)$	$\mathcal{O}_{Nq}$	$(\overline{N}_\alpha\gamma_\mu N_\beta)(\bar{q}_\gamma\gamma^\mu q_\delta)$	$\mathcal{O}_{lNqd}$	$(\bar{l}^j_\alpha N_\beta)\epsilon_{jk}(\bar{q}^k_\gamma d_\delta)$
$\mathcal{O}_{Nd}$	$(\overline{N}_\alpha\gamma_\mu N_\beta)(\bar{d}_\gamma\gamma^\mu d_\delta)$			$\mathcal{O}'_{lNqd}$	$(\bar{l}^j_\alpha\sigma_{\mu\nu}N_\beta)\epsilon_{jk}(\bar{q}^k_\gamma\sigma^{\mu\nu}d_\delta)$
$\mathcal{O}_{eNud}$	$(\bar{e}_\alpha\gamma_\mu N_\beta)(\bar{u}_\gamma\gamma^\mu d_\delta)$			$\mathcal{O}_{lNuq}$	$(\bar{l}^j_\alpha N_\beta)(\bar{u}_\gamma q^j_\delta)$

NSI

focus in this work

Table 1

j	$\overset{(\sim)}{\epsilon}_j$	$\mathcal{O}_j$	$\mathcal{O}'_j$
1	ϵ_L	$\gamma_\mu(\mathbb{1}-\gamma^5)$	$\gamma^\mu(\mathbb{1}-\gamma^5)$
2	$\tilde{\epsilon}_L$	$\gamma_\mu(\mathbb{1}+\gamma^5)$	$\gamma^\mu(\mathbb{1}-\gamma^5)$
3	ϵ_R	$\gamma_\mu(\mathbb{1}-\gamma^5)$	$\gamma^\mu(\mathbb{1}+\gamma^5)$
4	$\tilde{\epsilon}_R$	$\gamma_\mu(\mathbb{1}+\gamma^5)$	$\gamma^\mu(\mathbb{1}+\gamma^5)$
5	ϵ_S	$(\mathbb{1}-\gamma^5)$	$\mathbb{1}$
6	$\tilde{\epsilon}_S$	$(\mathbb{1}+\gamma^5)$	$\mathbb{1}$
7	$-\epsilon_P$	$(\mathbb{1}-\gamma^5)$	γ^5
8	$-\tilde{\epsilon}_P$	$(\mathbb{1}+\gamma^5)$	γ^5
9	ϵ_T	$\sigma_{\mu\nu}(\mathbb{1}-\gamma^5)$	$\sigma^{\mu\nu}(\mathbb{1}-\gamma^5)$
10	$\tilde{\epsilon}_T$	$\sigma_{\mu\nu}(\mathbb{1}+\gamma^5)$	$\sigma^{\mu\nu}(\mathbb{1}+\gamma^5)$

Table 2

$$L_{\rm SMNEFT} \supset 2\sqrt{2}G_F\sum_i C_i O_i\,, \quad (1)$$

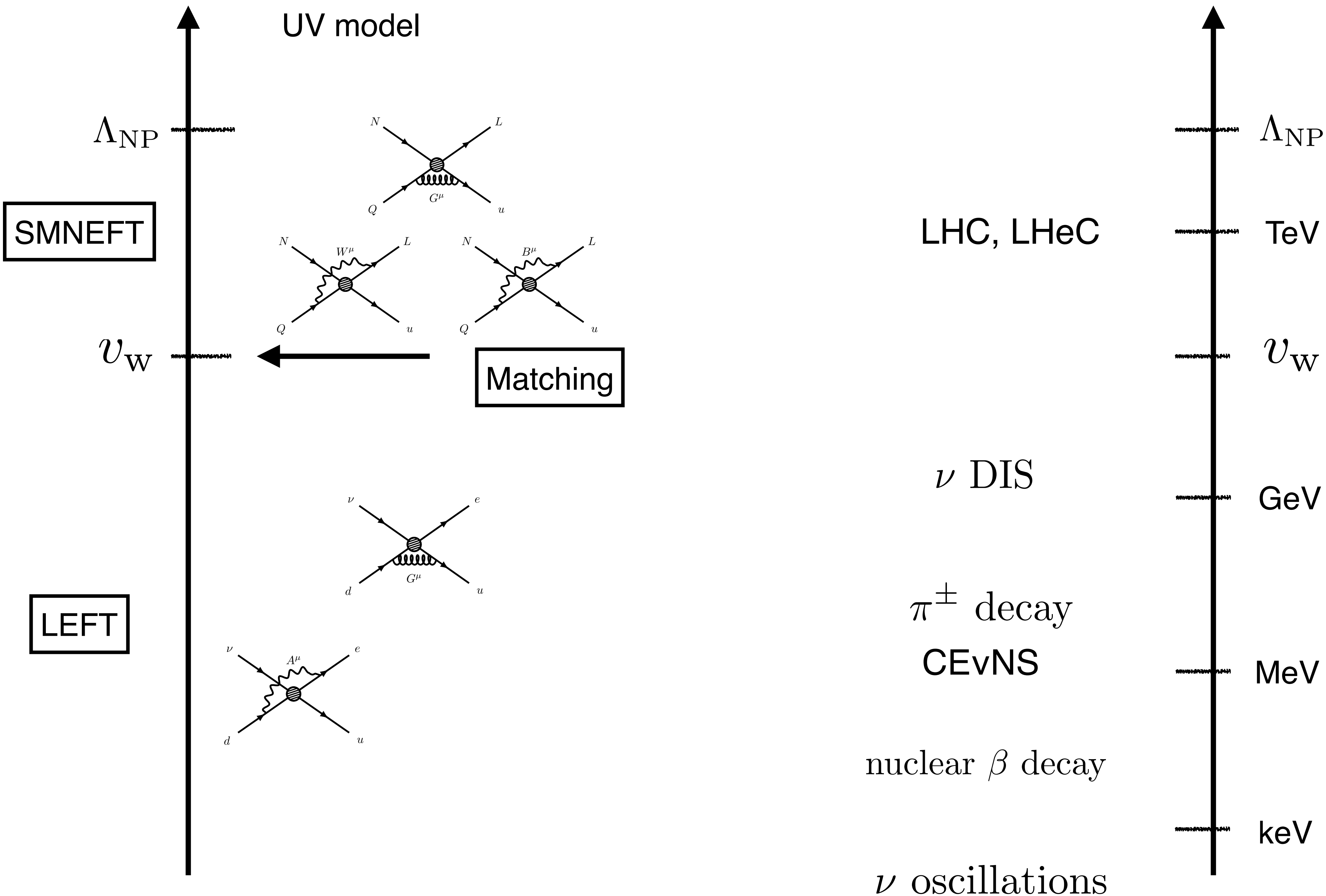
$$C \sim \kappa^2\frac{v^2}{\Lambda^2} \sim 10^{-4}(\kappa=1, \Lambda = 10\ {\rm TeV})$$

$$L^{\rm NC}_{\rm GNI} = -\frac{G_F}{\sqrt{2}}\sum_{j=1}^{10}(\overset{(\sim)}{\epsilon}_{j,q})^{\alpha\beta\gamma\delta}(\overline{\nu}_\alpha O_j\nu_\beta)(\overline{q}_\gamma O'_j q_\delta)$$

$$L^{\rm CC}_{\rm GNI} = -\frac{G_F V_{\gamma\delta}}{\sqrt{2}}\sum_{j=1}^{10}(\overset{(\sim)}{\epsilon}_{j,ud})^{\alpha\beta\gamma\delta}(\overline{\ell}_\alpha O_j\nu_\beta)(\overline{u}_\gamma O'_j d_\delta) + {\rm h.c.} \quad (2)$$

EFT

Experiments



RG Running

Anomalous dimension matrix for SMNEFT WCs

$$\mu\frac{d}{d\mu}\begin{pmatrix} C_{NLQu} \\ C_{NLdQ} \\ C'_{NLdQ} \end{pmatrix}_{(\mu)} = [\frac{\alpha_1(\mu)}{2\pi}\begin{pmatrix} -1/3 & 0 & 0 \\ 0 & 1/6 & -1 \\ 0 & -1/48 & -5/9 \end{pmatrix} + \frac{\alpha_2(\mu)}{2\pi}\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 9 \\ 0 & 3/16 & -3/2 \end{pmatrix} + \frac{\alpha_3(\mu)}{2\pi}\begin{pmatrix} -4 & 0 & 0 \\ 0 & -4 & 0 \\ 0 & 0 & 4/3 \end{pmatrix}]\begin{pmatrix} C_{NLQu} \\ C_{NLdQ} \\ C'_{NLdQ} \end{pmatrix}_{(\mu)}, \quad (1)$$

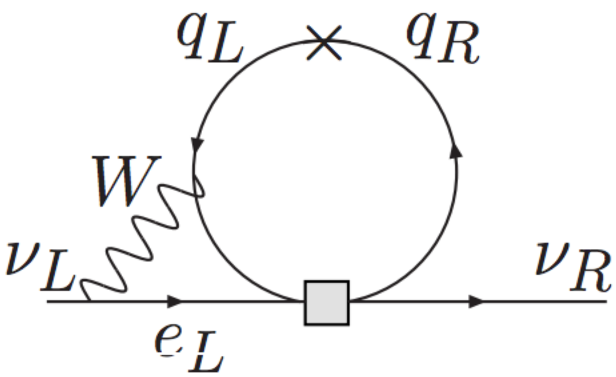
Anomalous dimension matrix for LEFT WCs

$$\mu\frac{d}{d\mu}\begin{pmatrix} \epsilon_{S,du} \\ \epsilon_{P,du} \\ \epsilon_{T,du} \end{pmatrix}_{(\mu)} = [\frac{\alpha_e(\mu)}{2\pi}\begin{pmatrix} 2/3 & 0 & 4 \\ 0 & 2/3 & 4 \\ 1/24 & 1/24 & -20/9 \end{pmatrix} + \frac{\alpha_3(\mu)}{2\pi}\begin{pmatrix} -4 & 0 & 0 \\ 0 & -4 & 0 \\ 0 & 0 & 4/3 \end{pmatrix}]\begin{pmatrix} \epsilon_{S,du} \\ \epsilon_{P,du} \\ \epsilon_{T,du} \end{pmatrix}_{(\mu)},$$

$$\mu\frac{d}{d\mu}\begin{pmatrix} \epsilon_{S,d} \\ \epsilon_{P,d} \\ \epsilon_{T,d} \end{pmatrix}_{(\mu)} = [\frac{\alpha_e(\mu)}{2\pi}\begin{pmatrix} -1/9 & 0 & 0 \\ 0 & -1/9 & 0 \\ 0 & 0 & 5/36 \end{pmatrix} + \frac{\alpha_3(\mu)}{2\pi}\begin{pmatrix} -4 & 0 & 0 \\ 0 & -4 & 0 \\ 0 & 0 & 4/3 \end{pmatrix}]\begin{pmatrix} \epsilon_{S,d} \\ \epsilon_{P,d} \\ \epsilon_{T,d} \end{pmatrix}_{(\mu)}, \quad (2)$$

$$\mu\frac{d}{d\mu}\begin{pmatrix} \epsilon_{S,u} \\ \epsilon_{P,u} \\ \epsilon_{T,u} \end{pmatrix}_{(\mu)} = [\frac{\alpha_e(\mu)}{2\pi}\begin{pmatrix} -4/9 & 0 & 0 \\ 0 & -4/9 & 0 \\ 0 & 0 & 5/9 \end{pmatrix} + \frac{\alpha_3(\mu)}{2\pi}\begin{pmatrix} -4 & 0 & 0 \\ 0 & -4 & 0 \\ 0 & 0 & 4/3 \end{pmatrix}]\begin{pmatrix} \epsilon_{S,u} \\ \epsilon_{P,u} \\ \epsilon_{T,u} \end{pmatrix}_{(\mu)},$$

Neutrino mass bounds



$$\Delta m_\nu^{\text{one-loop}} \simeq 3 G_F \epsilon \frac{m_q^3}{(4\pi)^2} (\ln \frac{\mu^2}{m_q^2}) \,,$$
$$\Delta m_\nu^{\text{two-loop}} \simeq 3 g^2 G_F \epsilon \frac{m_q M_W^2}{(4\pi)^4} (\ln \frac{\mu^2}{M_W^2})^2 \qquad (1)$$

[arxiv:0410254, 0409193]

kinematic bound: $m_\nu \lesssim 1.1\,\text{eV}$ [arXiv: 1909.06048] (2)

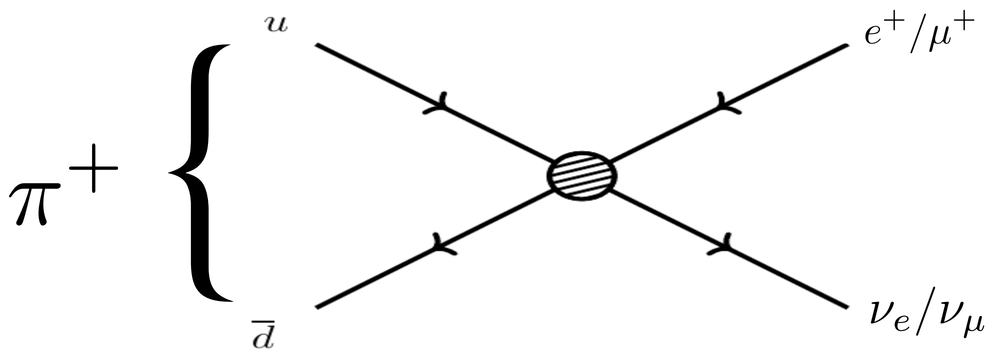
dynamic bound: $\sum m_\nu \lesssim 0.3\,\text{eV}$ [arXiv: 1811.02578] (3)

The bounds from neutrino mass without (with) cosmological inputs

$\delta m_\nu < \sum m_\nu \Rightarrow$ $|\, \epsilon_{S,P,T}^{\alpha\alpha 11} \,| \lesssim 10^{-3} (10^{-4})$ (4)

$|\, \epsilon_{S,P,T}^{\alpha\alpha 22} \,| \lesssim 10^{-5} (10^{-6})$ $|\, \epsilon_{S,P,T}^{\alpha\alpha 33} \,| \lesssim 10^{-10} (10^{-11})$

Charged pion decay



$$\Gamma^{\ell}_{\rm SM}(P \to \ell_\alpha \nu) \propto m_\ell^2 \qquad (1)$$

$$\Gamma^{\ell}_{\rm GNI,P}(P \to \ell_\alpha \nu) \propto (\epsilon^{\alpha\alpha 11}_{P,du})^2 \frac{m_\pi^4}{(m_u + m_d)^2} \qquad (2)$$

Electron decay channel of charged pion decay is very sensitive to the GNI

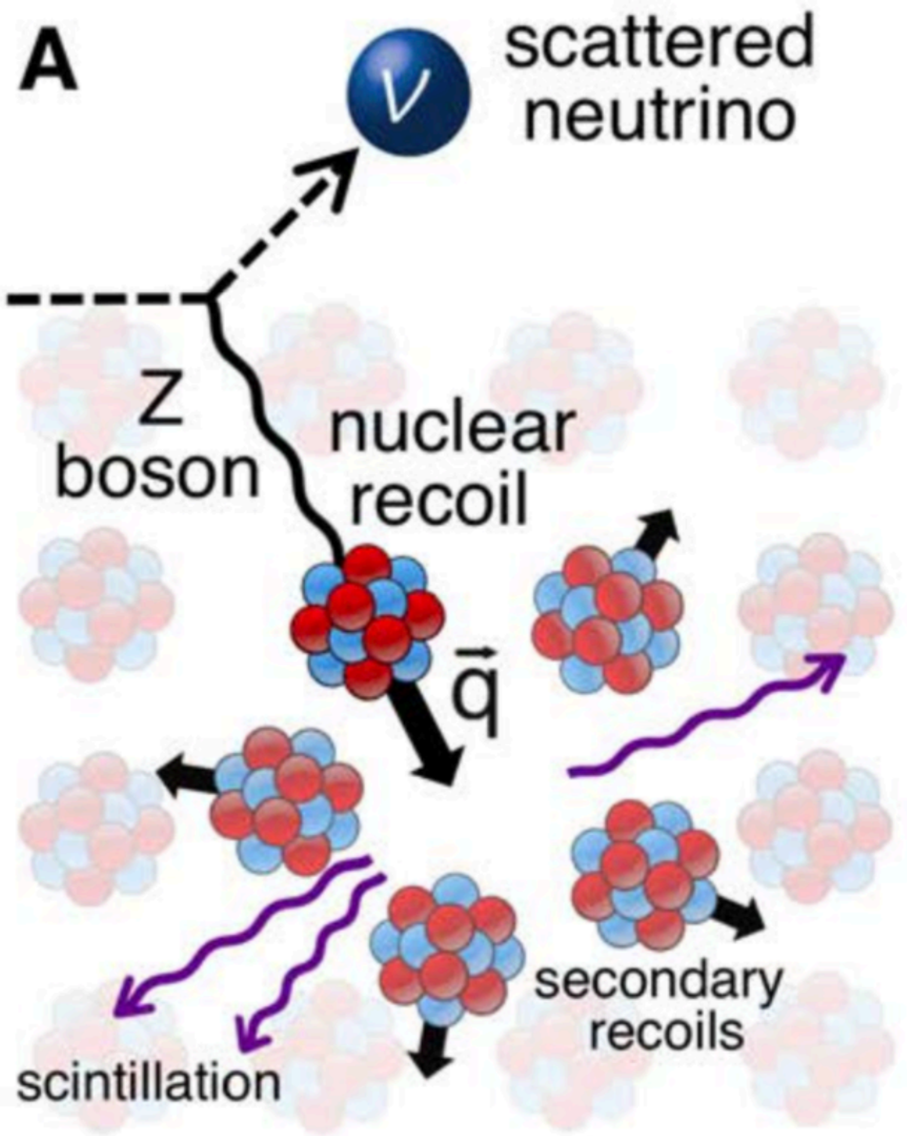
$$\frac{\Gamma^{\ell}_{\rm GNI,P}}{\Gamma^{\ell}_{\rm SM}} = (\epsilon^{\alpha\alpha 11}_{p,du})^2 \frac{m_\pi^4}{m_\ell^2 (m_u + m_d)^2} \qquad (3)$$

90% C.L. bounds on the individual SMNEFT WCs by setting the other two to zero

$$| C^{ee11}_{LNuq} |< 3.3 \times 10^{-6}, | C^{ee11}_{LNqd} |< 3.4 \times 10^{-6}, | C'^{ee11}_{LNqd} |< 3.9 \times 10^{-5}$$

$$| C^{\mu\mu 11}_{LNuq} |< 1.5 \times 10^{-3}, | C^{\mu\mu 11}_{LNqd} |< 1.5 \times 10^{-3}, | C'^{\mu\mu 11}_{LNqd} |< 1.7 \times 10^{-2} \qquad (4)$$

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS)



[arxiv:1708.01294]

When the momentum exchanged is smaller than the inverse of the nuclear size,

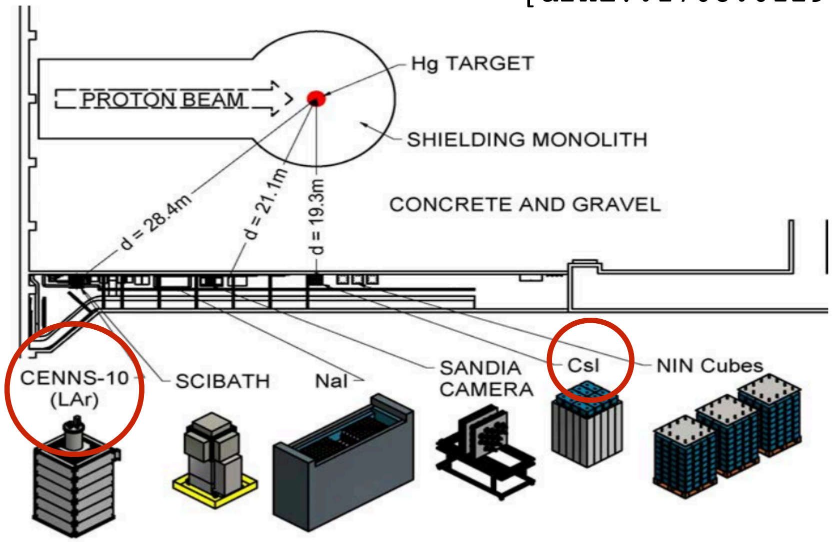
$$\frac{1}{E_\nu} \sim 10^{-14} m \rightarrow E_\nu \sim 20\mathrm{MeV}$$

the probability of interaction would be enhanced by the square of the number of neutrons in the nucleus.

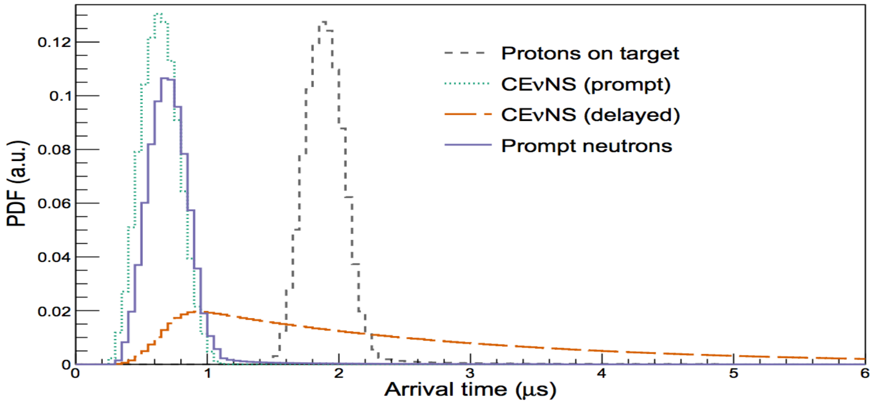
$$E_r \sim \frac{E_\nu^2}{M_{\mathrm{LAr}}} \sim 10\ \mathrm{KeV}$$

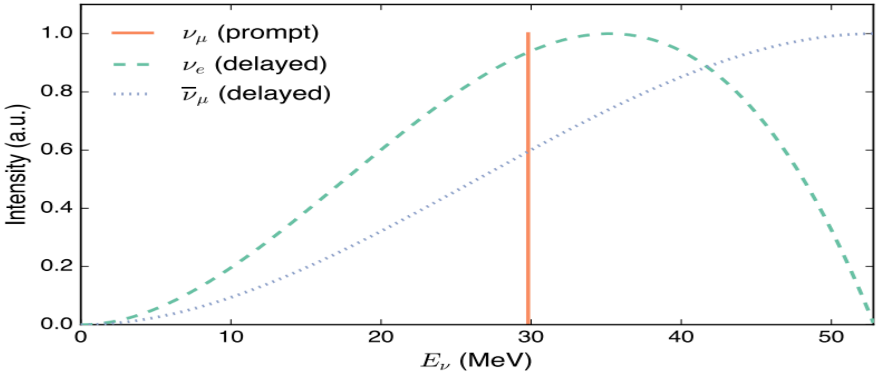
CEvNS

[arxiv:1708.01294]



[arxiv:1804.09459]





Temporal distribution

$$\pi^+ \to \mu^+ + \nu_\mu$$ prompt neutrino

$$\hookrightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

delayed neutrino

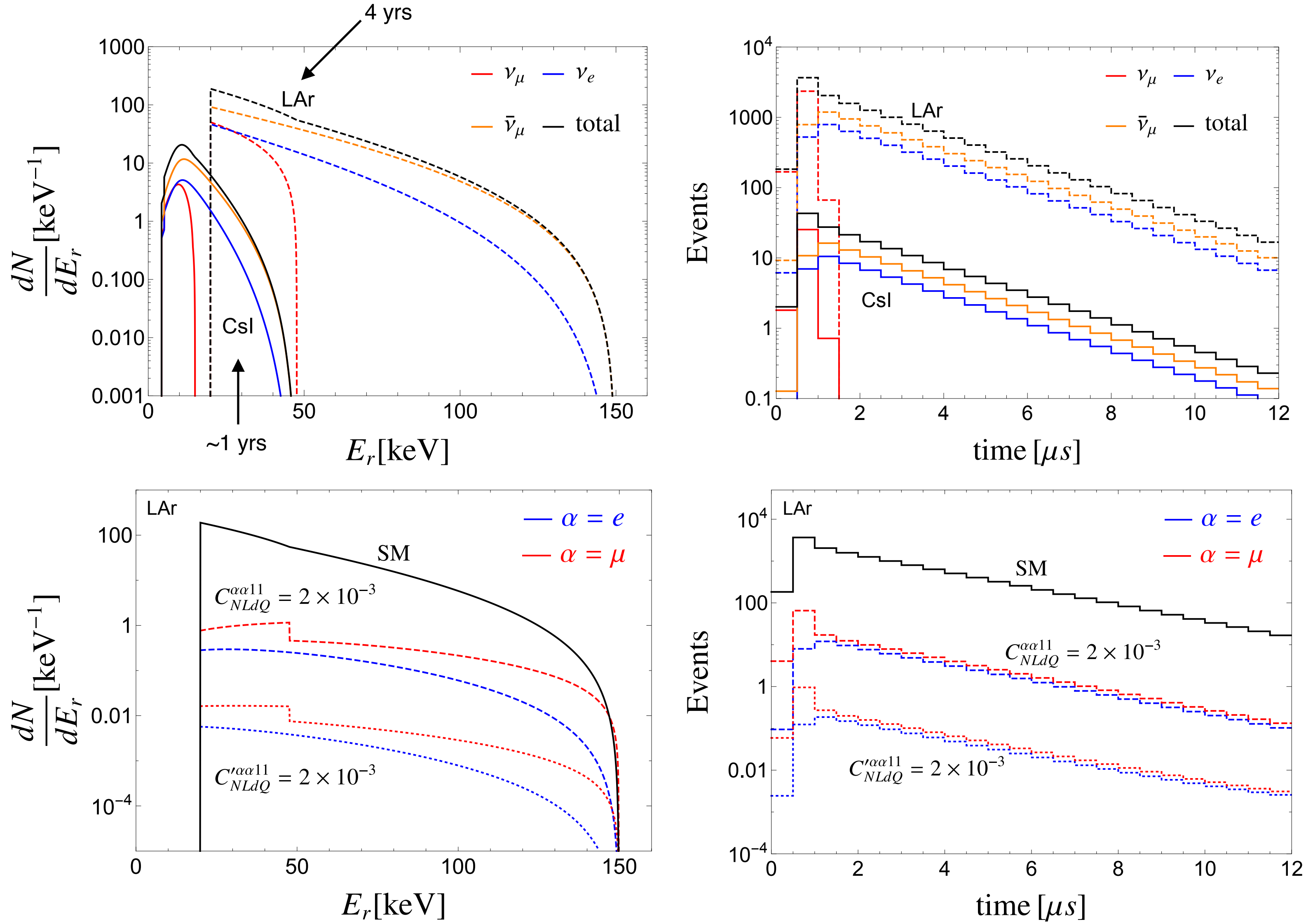
Energy distribution

$$\phi_{\nu_\mu}(E_\nu) = N\delta(E_\nu - \frac{m_\pi^2 - m_\mu^2}{2m_\pi})$$

$$\phi_{\bar{\nu}_\mu}(E_\nu) = N\frac{64E_\nu^2}{m_\mu^3}(\frac{3}{4} - \frac{E_\nu}{m_\mu})$$

$$\phi_{\nu_e}(E_\nu) = N\frac{192E_\nu^2}{m_\mu^3}(\frac{1}{2} - \frac{E_\nu}{m_\mu})$$

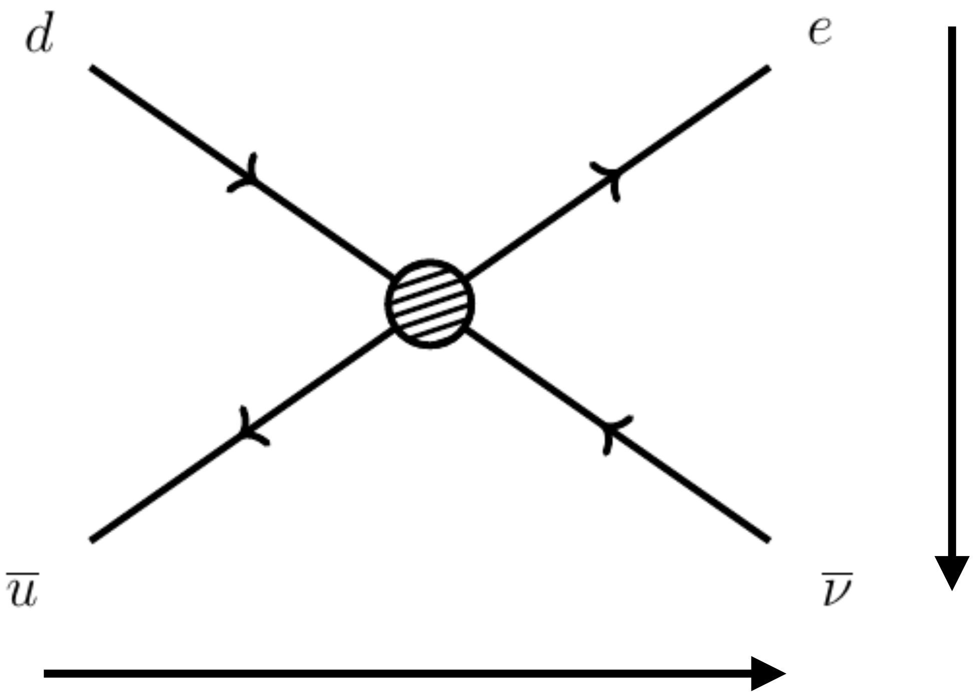
CEvNS



Current (projected) 90% C.L. bounds on the individual WCs, after setting the others to zero

$$|\ C^{ee11}_{NLQu}\ | < 4.0 \times 10^{-2}\,(3.0 \times 10^{-3})\,, \quad |\ C^{\mu\mu 11}_{NLQu}\ | < 4.3 \times 10^{-2}\,(1.9 \times 10^{-3}),$$
$$|\ C^{ee11}_{NLdQ}\ | < 4.8 \times 10^{-2}(3.6 \times 10^{-3})\,, \quad |\ C^{\mu\mu 11}_{NLdQ}\ | < 5.1 \times 10^{-2}\,(2.2 \times 10^{-3}),$$
$$|\ C'^{ee11}_{NLdQ}\ | < 2.0 \times 10^{-1}\,(2.9 \times 10^{-2})\,, \quad |\ C'^{\mu\mu 11}_{NLdQ}\ | < 1.9 \times 10^{-1}\,(1.9 \times 10^{-2})\,.$$

Collider Constraints



ep colliders:
jet + MET

pp colliders:
charged lepton + MET

Collider Constraints

$$\text{LHC}: \quad \hat{\sigma}_S = \frac{G_F^2 \hat{s}}{24\pi} C_S^2\,, \quad \hat{\sigma}_T = \frac{2G_F^2 \hat{s}}{9\pi} C_T^2\,, \quad \hat{\sigma}_{SM}(u\bar{d} \to W^* \to \mu^+ \nu_\mu) = \frac{G_F^2 \hat{s}}{18\pi} \frac{M_W^4}{(\hat{s} - M_W^2)^2}$$

$$\text{LHeC}: \quad \hat{\sigma}_S = \frac{G_F^2 \hat{s}}{24\pi} C_S^2\,, \quad \hat{\sigma}_T = \frac{14G_F^2 \hat{s}}{3\pi} C_T^2\,, \quad \hat{\sigma}_{SM}(eq \to \nu_e q') = \frac{G_F^2 \hat{s}}{2\pi} \frac{M_W^2}{\hat{s} + M_W^2}\,, \tag{1}$$

LHeC is much more sensitive to the tensor interactions

$$\text{At LHC}: \quad \hat{\sigma}_T / \hat{\sigma}_S = 16/3,$$
$$\text{At LHeC}: \quad \hat{\sigma}_T / \hat{\sigma}_S = 112. \tag{2}$$

Interference between scalar and tensor interactions

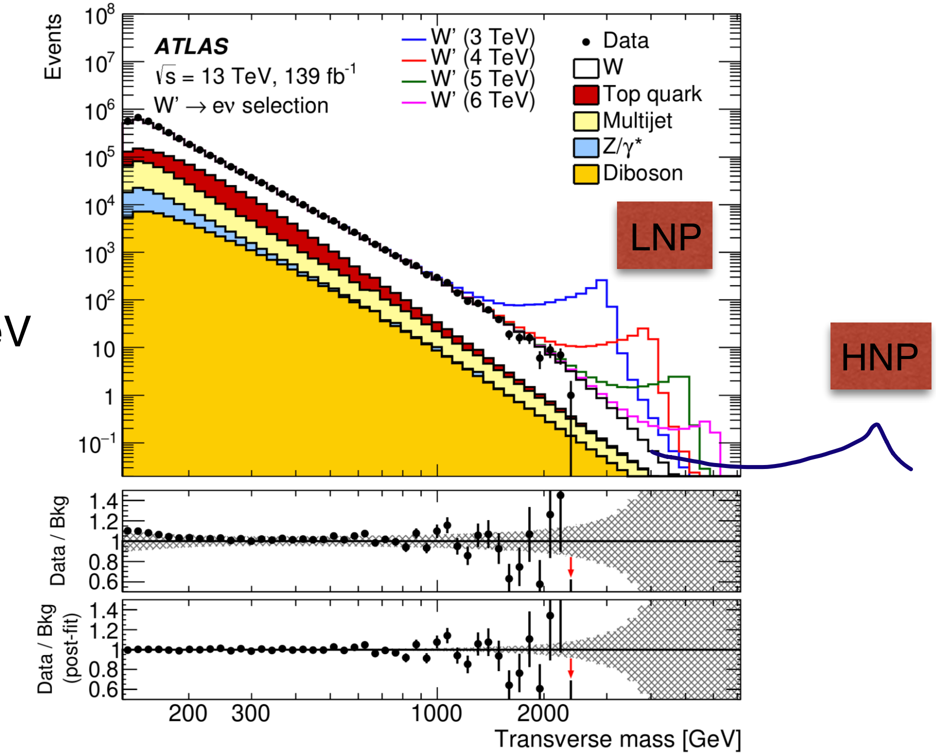
$$\text{LHC:} \quad \frac{d\hat{\sigma}_{ST}}{d\cos\theta^*} = \frac{G_F^2 \hat{s}}{12\pi}(C_S^* C_T + C_T^* C_S)\cos\theta^*\,, \quad (\cos\theta^* \to 0)$$

$$\text{LHeC:} \quad \frac{d\hat{\sigma}_{ST}}{d\cos\theta^*} = \frac{G_F^2 \hat{s}}{16\pi}(C_S^* C_T + C_T^* C_S)(\cos^2\theta^* - 2\cos\theta^* - 3) \tag{3}$$

Current bounds from the LHC

Two scenarios:

- Low-scale NP (LNP): use the distributions below 800 GeV
- High-scale NP (HNP): use the whole distributions



[arXiv:1906.05609]

90% C.L. bounds on LNP(HNP):

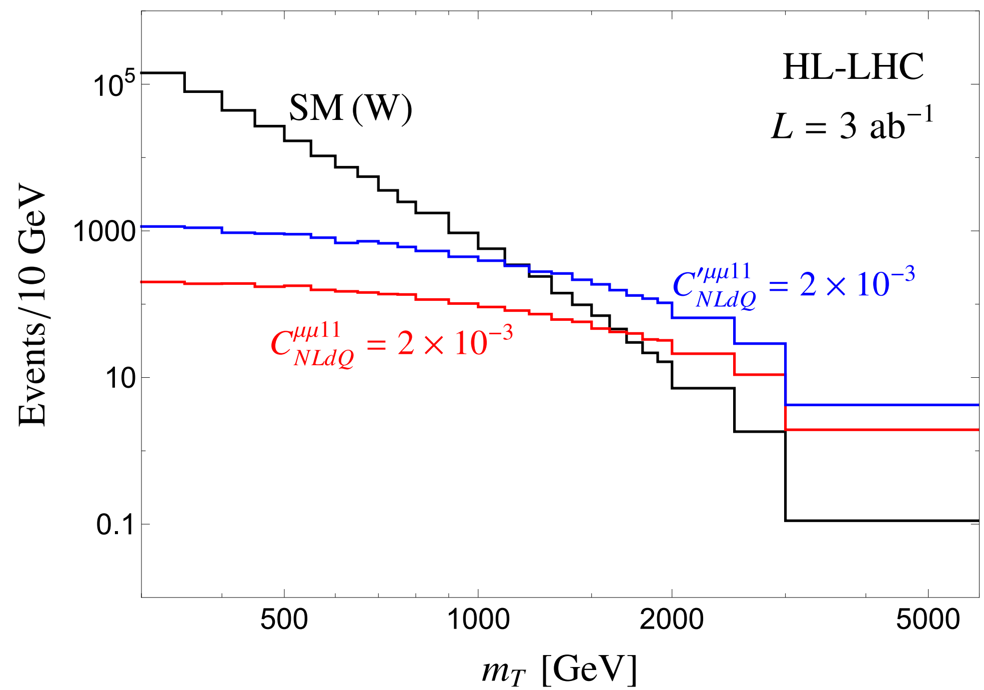
$$| C^{ee11}_{NLQu} | < 2.5\,(0.44) \times 10^{-3}\,,\, | C^{ee11}_{NLdQ} | < 2.6\,(0.46) \times 10^{-3}\,,\, | C'^{ee11}_{NLdQ} | < 1.2\,(0.24) \times 10^{-3}$$

$$| C^{\mu\mu 11}_{NLQu} | < 2.9\,(0.66) \times 10^{-3}\,,\, | C^{\mu\mu 11}_{NLdQ} | < 3.0\,(0.68) \times 10^{-3}\,,\, | C'^{\mu\mu 11}_{NLdQ} | < 1.4\,(0.40) \times 10^{-3}$$

Projections from the HL-LHC and LHeC

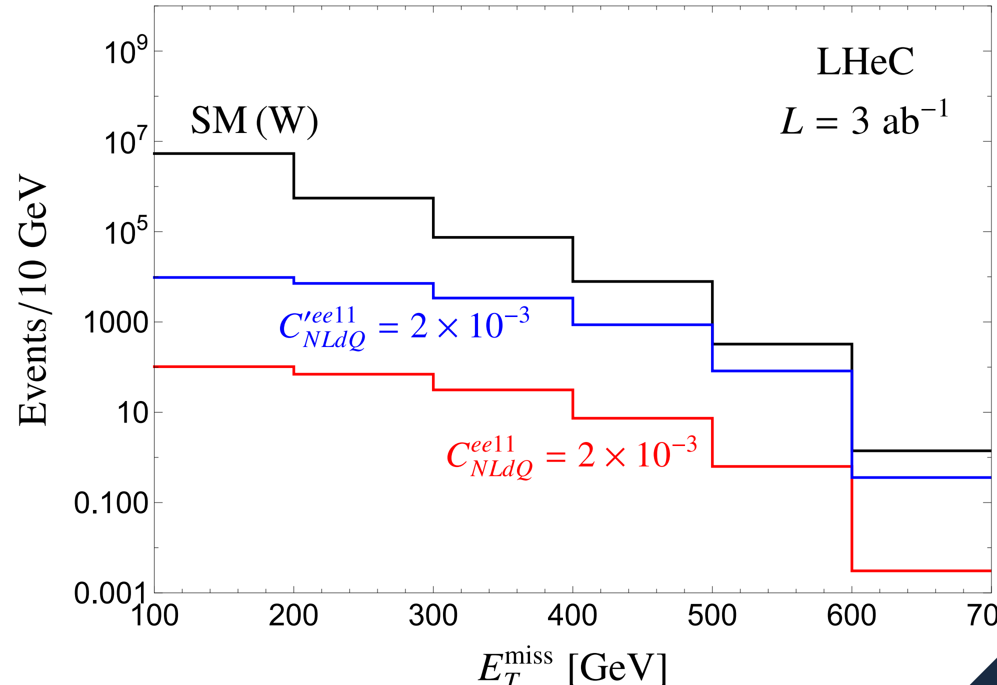
HL-LHC 90% C.L. bounds with $3\,\mathrm{ab}^{-1}$ on LNP (HNP)

$$|\, C^{ee11}_{NLQu} \,| < 2.3\,(0.28) \times 10^{-3},\ |\, C^{\mu\mu11}_{NLQu} \,| < 2.7\,(0.28) \times 10^{-3},$$
$$|\, C^{ee11}_{NLdQ} \,| < 2.4\,(0.28) \times 10^{-3},\ |\, C^{\mu\mu11}_{NLdQ} \,| < 2.8\,(0.29) \times 10^{-3},$$
$$|\, C'^{ee11}_{NLdQ} \,| < 1.1\,(0.18) \times 10^{-3},\ |\, C'^{\mu\mu11}_{NLdQ} \,| < 1.3\,(0.18) \times 10^{-3}$$



LHeC 90% C.L. bounds with $3\,\mathrm{ab}^{-1}$

$$|\, C^{ee11}_{NLQu} \,| < 3.9 \times 10^{-3},$$
$$|\, C^{ee11}_{NLdQ} \,| < 6.1 \times 10^{-3},$$
$$|\, C'^{ee11}_{NLdQ} \,| < 0.58 \times 10^{-3}$$



Results

Current 90% C.L. bounds on the SMNEFT WCs at 1 TeV

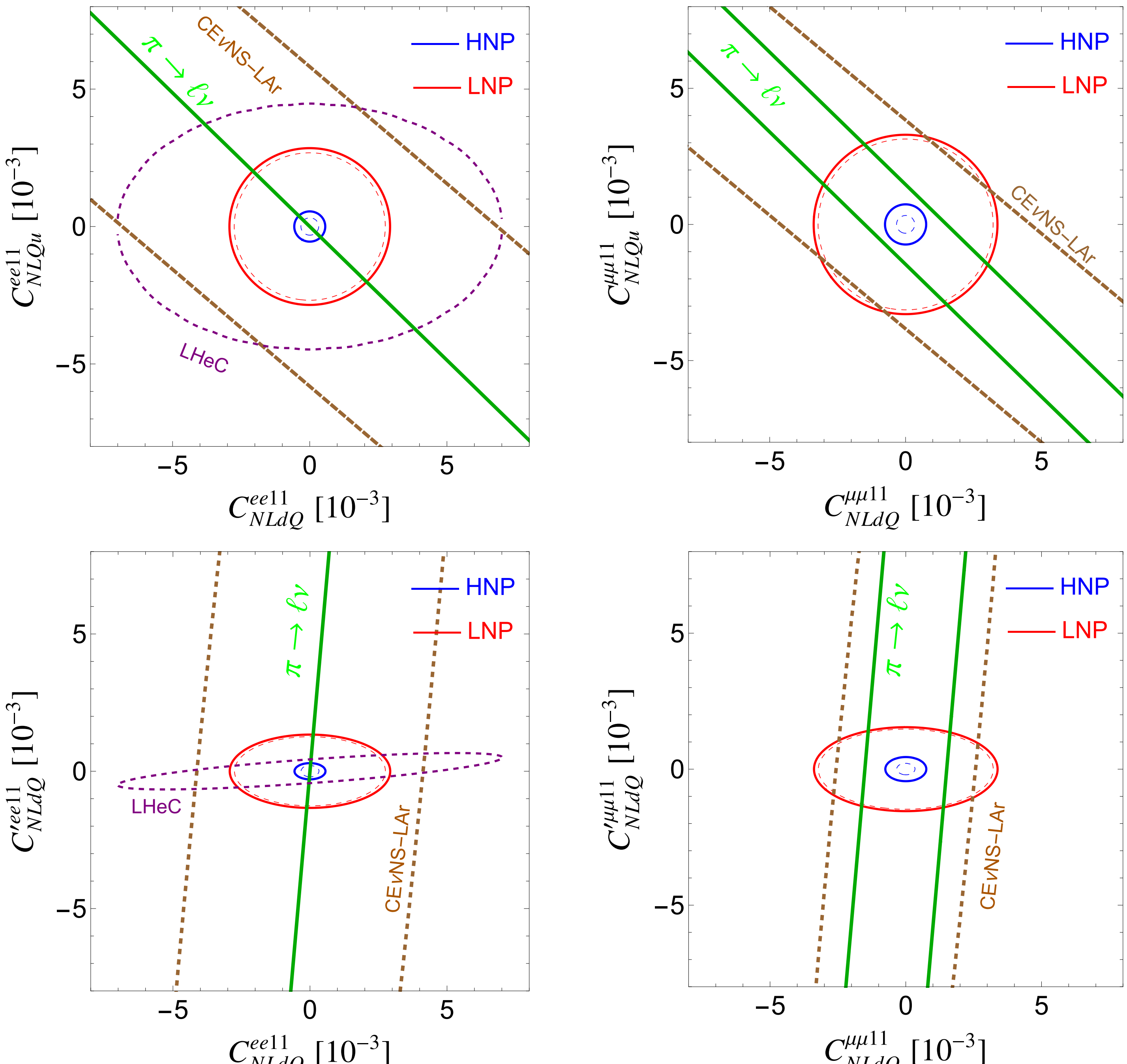
WC	π^+ decay	β decay	ν DIS	CEνNS	HERA	LHC: LNP(HNP)
C_{NLQu}^{ee11}	3.3×10^{-6}	3.4×10^{-2}	0.77	4.0×10^{-2}	$\sim \mathbf{5}$	$\mathbf{2.5\,(0.44) \times 10^{-3}}$
C_{NLdQ}^{ee11}	3.4×10^{-6}	3.5×10^{-2}	0.75	4.8×10^{-2}	$\sim \mathbf{5}$	$\mathbf{2.6\,(0.46) \times 10^{-3}}$
$C_{NLdQ}^{\prime ee11}$	3.9×10^{-5}	2.8×10^{-2}	0.15	0.2	$\sim \mathbf{5}$	$\mathbf{1.2\,(0.24) \times 10^{-3}}$
$C_{NLQu}^{\mu\mu11}$	1.5×10^{-3}	-	$\mathbf{7.8 \times 10^{-2}}$	4.3×10^{-2}	-	$\mathbf{2.9\,(0.66) \times 10^{-3}}$
$C_{NLdQ}^{\mu\mu11}$	1.5×10^{-3}	-	$\mathbf{7.6 \times 10^{-2}}$	5.1×10^{-2}	-	$\mathbf{3.0\,(0.68) \times 10^{-3}}$
$C_{NLdQ}^{\prime \mu\mu11}$	1.7×10^{-2}	-	$\mathbf{1.5 \times 10^{-2}}$	0.19	-	$\mathbf{1.4\,(0.40) \times 10^{-3}}$

Future 90% C.L. bounds on the SMNEFT WCs at 1 TeV

WC	CEνNS-LAr	LHeC	HL-LHC: LNP(HNP)
C_{NLQu}^{ee11}	3.0×10^{-3}	$\mathbf{3.9 \times 10^{-3}}$	$\mathbf{2.3\,(0.28) \times 10^{-3}}$
C_{NLdQ}^{ee11}	3.6×10^{-3}	$\mathbf{6.1 \times 10^{-3}}$	$\mathbf{2.4\,(0.28) \times 10^{-3}}$
$C_{NLdQ}^{\prime ee11}$	2.9×10^{-2}	$\mathbf{0.58 \times 10^{-3}}$	$\mathbf{1.1\,(0.18) \times 10^{-3}}$
$C_{NLQu}^{\mu\mu11}$	1.9×10^{-3}	-	$\mathbf{2.7\,(0.28) \times 10^{-3}}$
$C_{NLdQ}^{\mu\mu11}$	2.2×10^{-3}	-	$\mathbf{2.8\,(0.29) \times 10^{-3}}$
$C_{NLdQ}^{\prime \mu\mu11}$	1.9×10^{-2}	-	$\mathbf{1.3\,(0.18) \times 10^{-3}}$

Results

The 90% C.L. allowed regions



- Low-energy probes and high-energy colliders are complementary

Conclusions

- Neutrino mass bounds indicate that the SMNEFT operators involving the second and third families of quarks are highly constrained. This conclusion, however, is model-dependent and can be evaded.
- Low-energy probes and high-energy colliders are complementary.
- Charged pion decay is extremely sensitive to the LEFT pseudoscalar operators. With the assumption of only one nonzero operator at a time, the bounds on the electron flavor are at the 10^{-6} level.
- The strongest current bounds on the three SMNEFT operators are from LHC charged lepton +missing transverse momentum, and are at the $10^{-4} - 10^{-3}$ level depending on the energy range of validity of the EFT.
- HL-LHC can improve the bounds by a factor of a few and reach 10^{-4} in the HNP case
- A future COHERENT experiment with LAr can set strong bounds on the scalar operators, comparable with that from the HL-LHC with the LNP assumption, especially when the muon flavor is involved.
- LHeC will be important to study tensor interactions involving the electron flavor, and can place bounds at the 10^{-4} level.

Thanks!

Back-up slides

SM Neutrino Interactions

$$L_{\rm SM}^{\rm NC} = -\frac{G_F}{\sqrt{2}}(\delta^{\alpha\beta}\delta^{\gamma\delta})(\bar{\nu}_\alpha\gamma_\mu(1-\gamma_5)\nu_\beta)(g_{L,f}\bar{f}_\gamma\gamma^\mu(1-\gamma_5)f_\delta + g_{R,f}\bar{f}_\gamma\gamma^\mu(1-\gamma_5)f_\delta),$$

$$L_{\rm SM}^{\rm CC} = -\frac{G_F}{\sqrt{2}}V_{\gamma\delta}(\delta^{\alpha\beta})(\bar{\ell}_\alpha\gamma_\mu(1-\gamma_5)\nu_\beta)(\bar{f}_\gamma\gamma^\mu(1-\gamma_5)f'_\delta)$$

f	e	u	d
$g_{L,f}$	$-\frac{1}{2}+\sin^2\theta_W$	$\frac{1}{2}-\frac{2}{3}\sin^2\theta_W$	$-\frac{1}{2}+\frac{1}{3}\sin^2\theta_W$
$g_{R,f}$	$\sin^2\theta_W$	$-\frac{2}{3}\sin^2\theta_W$	$\frac{1}{3}\sin^2\theta_W$

Tree-level Matching

Matching is performed at the weak scale

CC

$$\begin{cases} \epsilon_{S,d}^{\alpha\beta\gamma\delta} = -C_{NLdQ}^{\alpha\beta\gamma\delta}\,, \quad \epsilon_{S,u}^{\alpha\beta\gamma\delta} = -C_{NLQu}^{\alpha\beta\rho\delta} V_{\rho\gamma}\,, \\ \epsilon_{P,d}^{\alpha\beta\gamma\delta} = -C_{NLdQ}^{\alpha\beta\gamma\delta}\,, \quad \epsilon_{P,u}^{\alpha\beta\gamma\delta} = C_{NLQu}^{\alpha\beta\rho\delta} V_{\rho\gamma}\,, \\ \epsilon_{T,d}^{\alpha\beta\gamma\delta} = -C_{NLdQ}^{\prime\alpha\beta\gamma\delta}\,, \end{cases}$$

NC

$$\begin{cases} \epsilon_{S,du}^{\alpha\beta\gamma\delta} = \dfrac{C_{NLdQ}^{\alpha\beta\gamma\rho} V_{\rho\delta}^{\dagger} - C_{NLQu}^{\alpha\beta\gamma\delta}}{V_{\delta\gamma}^{*}}\,, \quad \epsilon_{P,du}^{\alpha\beta\gamma\delta} = \dfrac{C_{NLdQ}^{\alpha\beta\gamma\rho} V_{\rho\delta}^{\dagger} + C_{NLQu}^{\alpha\beta\gamma\delta}}{V_{\delta\gamma}^{*}}\,, \\ \epsilon_{T,du}^{\alpha\beta\gamma\delta} = C_{NLdQ}^{\prime\alpha\beta\gamma\rho} \dfrac{V_{\rho\delta}^{\dagger}}{V_{\delta\gamma}^{*}}\,. \end{cases}$$

- Both neutral and charged current interactions are induced by each of the three SMNEFT operators.

Matching and Running

After the integration

$$\begin{pmatrix} C_{NLQu} \\ C_{NLdQ} \\ C'_{NLdQ} \end{pmatrix}_{(\mu=M_Z)} = \begin{pmatrix} 1.18 & 0 & 0 \\ 0 & 1.18 & -0.117 \\ 0 & -2.44\times 10^{-3} & 0.966 \end{pmatrix} \begin{pmatrix} C_{NLQu} \\ C_{NLdQ} \\ C'_{NLdQ} \end{pmatrix}_{(\mu=1\ \mathrm{TeV})},$$

$$\begin{pmatrix} \epsilon_{S,du} \\ \epsilon_{P,du} \\ \epsilon_{T,du} \end{pmatrix}_{(\mu=2\ \mathrm{GeV})} = \begin{pmatrix} 1.52 & 2.34\times 10^{-6} & -0.0218 \\ 2.34\times 10^{-6} & 1.52 & -0.0218 \\ -2.26\times 10^{-4} & -2.26\times 10^{-4} & 0.878 \end{pmatrix} \begin{pmatrix} \epsilon_{S,du} \\ \epsilon_{P,du} \\ \epsilon_{T,du} \end{pmatrix}_{(\mu=M_Z)},$$

$$\begin{pmatrix} \epsilon_{S,d} \\ \epsilon_{P,d} \\ \epsilon_{T,d} \end{pmatrix}_{(\mu=2\ \mathrm{GeV})} = \begin{pmatrix} 1.52 & 0 & 0 \\ 0 & 1.52 & 0 \\ 0 & 0 & 0.869 \end{pmatrix} \begin{pmatrix} \epsilon_{S,d} \\ \epsilon_{P,d} \\ \epsilon_{T,d} \end{pmatrix}_{(\mu=M_Z)},$$

$$\begin{pmatrix} \epsilon_{S,u} \\ \epsilon_{P,u} \\ \epsilon_{T,u} \end{pmatrix}_{(\mu=2\ \mathrm{GeV})} = \begin{pmatrix} 1.53 & 0 & 0 \\ 0 & 1.53 & 0 \\ 0 & 0 & 0.867 \end{pmatrix} \begin{pmatrix} \epsilon_{S,u} \\ \epsilon_{P,u} \\ \epsilon_{T,u} \end{pmatrix}_{(\mu=M_Z)}.$$

Neutrino Deep Inelastic Scattering

Assumptions: isoscalar target, free nucleons

CHARM

$$R^e \equiv \frac{\sigma(\nu_e N \to \nu X) + \sigma(\overline{\nu}_e N \to \nu X)}{\sigma(\nu_e N \to e^- X) + \sigma(\overline{\nu}_e N \to e^+ X)} = 0.406 \pm 0.140$$

GNI prediction:

$$R^e = g_L^2 + g_R^2 + \frac{1}{12} \sum_{q=u,d} ((\epsilon_{s,q}^{ee11})^2 + (\epsilon_{p,q}^{ee11})^2 + 224(\epsilon_{T,q}^{ee11})^2)$$

$$g_L^2 = g_{L,u}^2 + g_{L,d}^2, \quad g_R^2 = g_{R,u}^2 + g_{R,d}^2.$$

Bound: $|\, C_{NLQu}^{ee11} \,| < 0.77\,, \quad |\, C_{NLdQ}^{ee11} \,| < 0.75\,, \quad |\, C_{NLdQ}^{\prime ee11} \,| < 0.15$

Neutrino Deep Inelastic Scattering

NuTeV

$$R^{\nu} \equiv \frac{\sigma(\nu_\mu N \to \nu X)}{\sigma(\nu N \to \mu^- X)} = 0.3916 \pm 0.0013$$

$$R^{\overline{\nu}} \equiv \frac{\sigma(\overline{\nu}_\mu N \to \overline{\nu} X)}{\sigma(\overline{\nu} N \to \mu^+ X)} = 0.4050 \pm 0.0027$$

NGI prediction:

$$R^{\nu} = \frac{(g_L^2 + \frac{1}{3}g_R^2)f_q + (\frac{1}{3}g_L^2 + g_R^2)f_{\bar{q}} + \frac{1}{24}\sum_{q=u,d}((\epsilon_{s,q}^{\mu\mu 11})^2 + (\epsilon_{p,q}^{\mu\mu 11})^2 + 224(\epsilon_{T,q}^{\mu\mu 11})^2)(f_q + f_{\bar{q}})}{f_q + \frac{1}{3}f_{\bar{q}}}$$

$$R^{\overline{\nu}} = \frac{(\frac{1}{3}g_L^2 + g_R^2)f_q + (g_L^2 + \frac{1}{3}g_R^2)f_{\bar{q}} + \frac{1}{24}\sum_{q=u,d}((\epsilon_{s,q}^{\mu\mu 11})^2 + (\epsilon_{p,q}^{\mu\mu 11})^2 + 224(\epsilon_{T,q}^{\mu\mu 11})^2)(f_q + f_{\bar{q}})}{\frac{1}{3}f_q + f_{\bar{q}}}$$

Our SM values (SM values after including charge asymmetry corrections, nuclear corrections…)

$$R^{\nu}_{SM} = 0.32(0.3950)$$

[W. Bentz, I. C. Cloet, J. T. Londergan, A. W. Thomas, 0908.3198]

$$R^{\overline{\nu}}_{SM} = 0.37(0.4066)$$

90% C.L. bounds: $\mid C_{NLQu}^{\mu\mu 11} \mid < 0.078\,, \quad \mid C_{NLdQ}^{\mu\mu 11} \mid < 0.076\,, \quad \mid C_{NLdQ}^{\prime\mu\mu 11} \mid < 0.015$

CEvNS targets

	Nuclear Target	Mass (kg)	Exposure	Recoil threshold (keVr)
Current	CsI	14.6	308.1 (day)	6.5
Future	LAr	610	4 (yr)	20

CEvNS

The differential cross section including scalar, vector, and tensor contribution reads

$$\frac{d\sigma_a^\alpha}{dT} = \frac{G_F^2}{4\pi} M_a N_a^2 [(\xi_S^\alpha)^2 \frac{T}{T_{max}} + (\xi_V^\alpha)^2 (1 - \frac{T}{T_{max}} - \frac{T}{E_\nu}) + (\xi_T^\alpha)^2 (1 - \frac{T}{2T_{max}} - \frac{T}{E_\nu})] F^2(q^2)$$

$$(\xi_S^\alpha)^2 = \frac{1}{N_a^2} \{ (\sum_{q=u,d} 2\mathrm{Re}(\epsilon_{S,q}^{\alpha\alpha 11})[N \frac{m_n}{m_q} f_{Tq}^n + Z \frac{m_p}{m_q} f_{Tq}^p])^2 + (\sum_{q=u,d} 2\mathrm{Im}(\epsilon_{S,q}^{\alpha\alpha 11})[N \frac{m_n}{m_q} f_{Tq}^n + Z \frac{m_p}{m_q} f_{Tq}^p])^2 \},$$

$$(\xi_V^\alpha)^2 = \frac{2}{N_a^2} (Z(2g_{V,u} + g_{V,d}) + N(g_{V,u} + 2g_{V,d}))^2,$$

$$(\xi_T^\alpha)^2 = \frac{8}{N_a^2} (\sum_{q=u,d} 4\,\mathrm{Re}(\epsilon_{T,q}^{\alpha\alpha 11})[Z\delta_q^p + N\delta_q^n])^2.$$

$$N_{th}(t, E_r, \epsilon) = \sum_{\alpha=e,\mu} \frac{m_{\det} N_A}{M_a} \int_{\Delta T} dT \int_{\Delta t} dt \rho_\alpha(t) \int_{E_\nu^{\min}}^{E_\nu^{\max}} dE_\nu \, \phi_\alpha(E_\nu) \frac{d\sigma_a^\alpha(\epsilon)}{dT}$$

Numerical values of the nuclear matrix elements

$$f_{Tu}^p = 0.019,\ f_{Td}^p = 0.041,\ f_{Tu}^n = 0.023,\ f_{Td}^n = 0.034$$
$$\delta_u^p = 0.54,\ \delta_d^p = -0.23,\ \delta_u^n = -0.23,\ \delta_d^n = 0.54.$$

Projections from the HL-LHC

Selection rules

- $p_T^{\mu(e)} > 55\,(65)$ GeV and $|\eta_\ell| < 2.4$,
- veto b-tagged jets,
- discard additional electron or muon with $p_T > 20$ GeV and $|\eta_\ell| < 2.4$,
- $m_T > 300$ GeV,

Systematic uncertainties

electron channel: $\sigma_e \sim 10\%\,(12\%)$ for $m_T = 300\,(2000)$ GeV;

muon channel: $\sigma_\mu \sim 10\%\,(17\%)$ for $m_T = 300\,(2000)$ GeV.

Current bounds from the HERA

The HERA collaboration set the bounds on the contact interaction $e\nu q q'$

in the charged current process: $e^{\pm} p \to \overset{(-)}{\nu} X$

Based on the distribution of Q^2 and x, the lower bounds on the contact term mass scales is around 1 TeV with strong coupling assumptions

[arXiv:9707299]

Bounds:

$$| \, C^{ee11}_{LNuq} \, |, | \, C^{ee11}_{LNqd} \, |, | \, C'^{ee11}_{LNqd} \, | \lesssim 5$$

Projections from the LHeC

Selection rules

- leading jet should have $p_T^j > 20\,\mathrm{GeV}$ and $|\eta_j| < 2.5$,
- veto any electrons with $p_T^e > 20\,\mathrm{GeV}$ and $|\eta_e| < 2.5$,
- the angular distance between jet and missing E_T should be bigger than 0.4,
- $E_T^{\mathrm{miss}} > 300\,\mathrm{GeV}$.