SMEFT induced neutrino non-standard interactions in the context of CEvNS and neutrino oscillations

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Magnificent CEvNS 2024, June 12, 2024, Valencia, Spain

Based on

2011.14292 and 2106.15800 in collaboration with H. Li, J. Tang, S. Vihonen, J-H Yu

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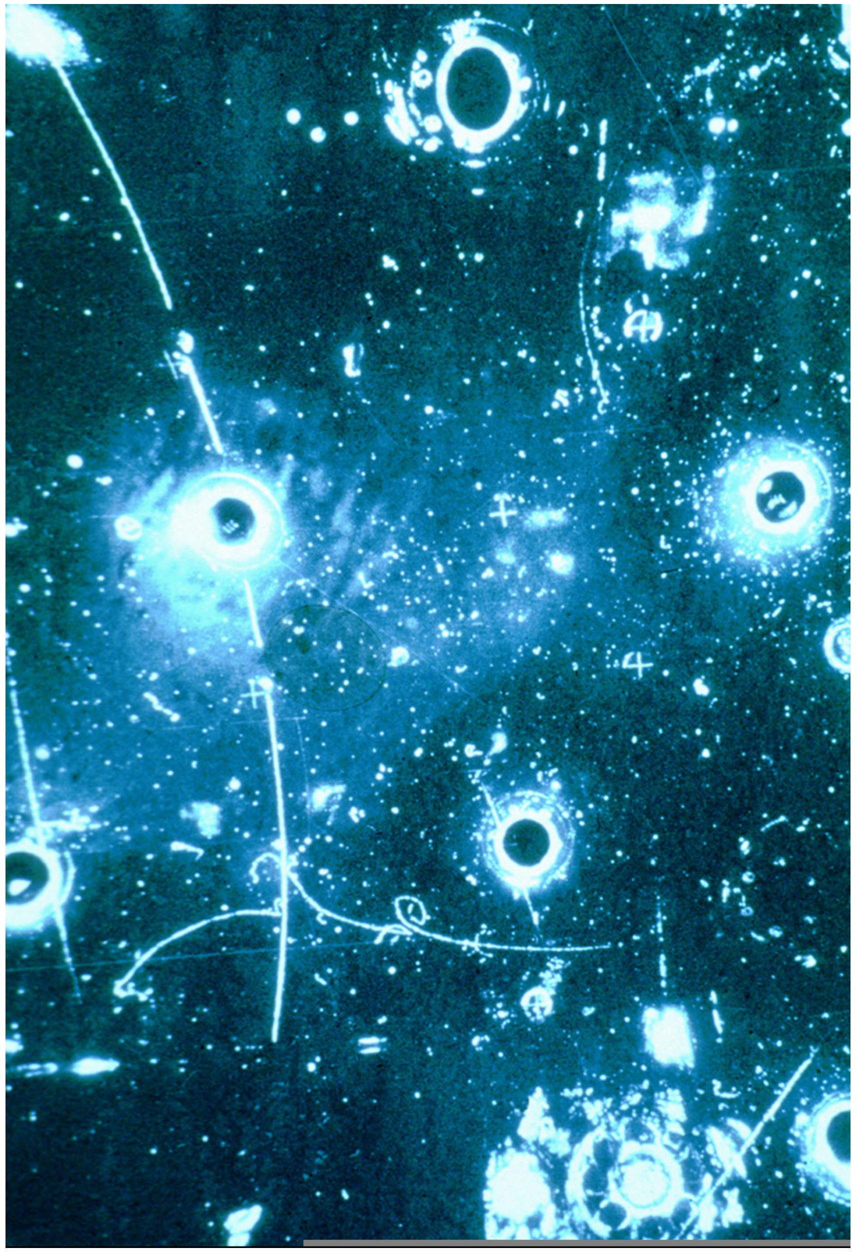
Introduction

First evidence for a neutral current process in 1973 that also paved the way for a later discovery of $W^{\pm}$ and Z at CERN in the 1980s

Gargamelle's priorities

1. W search
2. deep inelastic scattering, scaling
3. current algebra sum rules, CVC, PCAC
4. Diagonal Model
5. $\Delta S = 1$ processes, inverse hyperon decay, $\overline{\nu_\mu} + p \rightarrow \Lambda + \mu^+$
6. inverse muon decay, $\nu_\mu + e^- \rightarrow \mu^- + \nu_e$
7. electron−muon universality
8. neutral-current search
9. form factors in exclusive reactions
10. search for heavy leptons

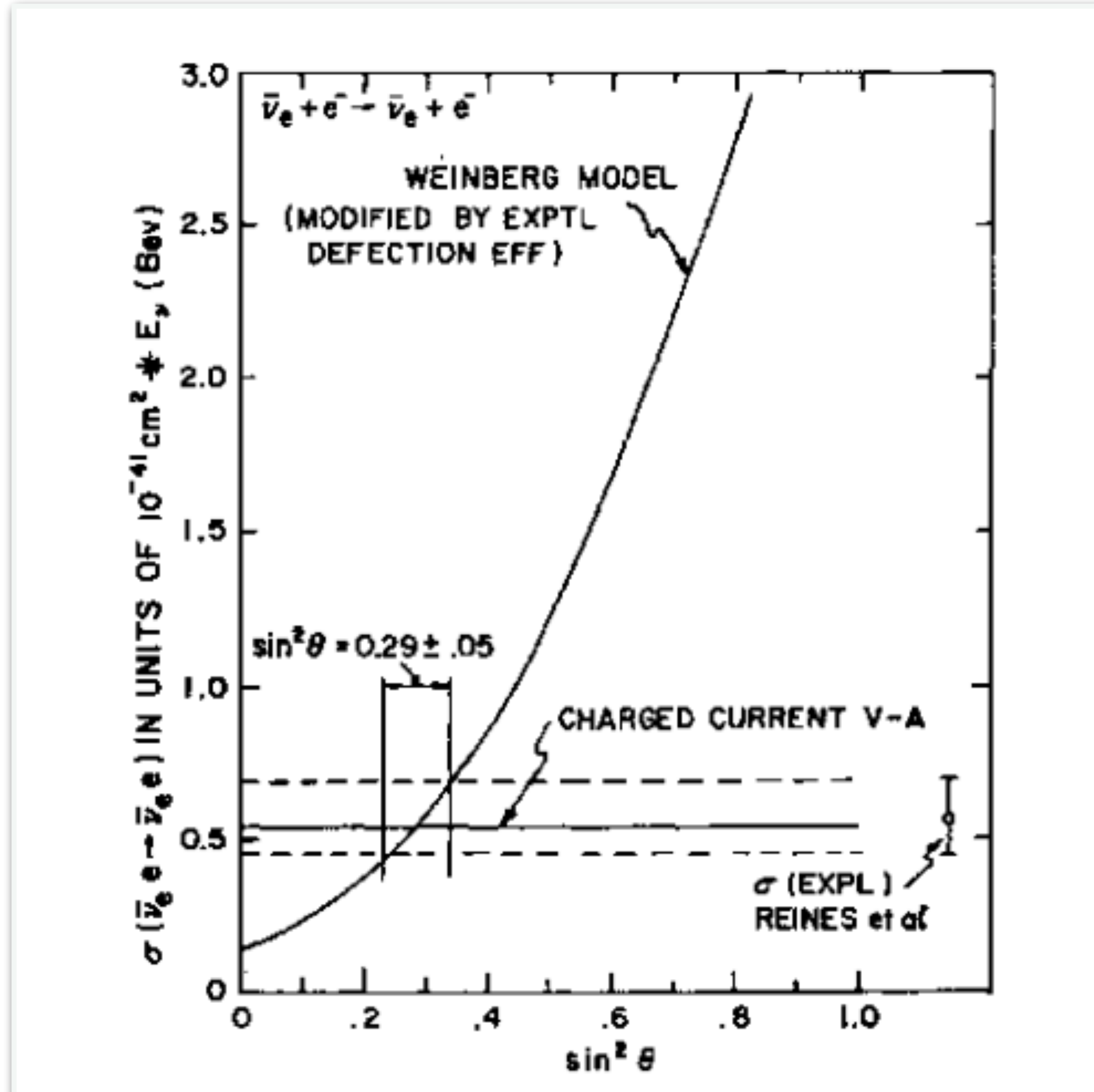


Introduction

Earlier results consistent with both V-A and the weak theory

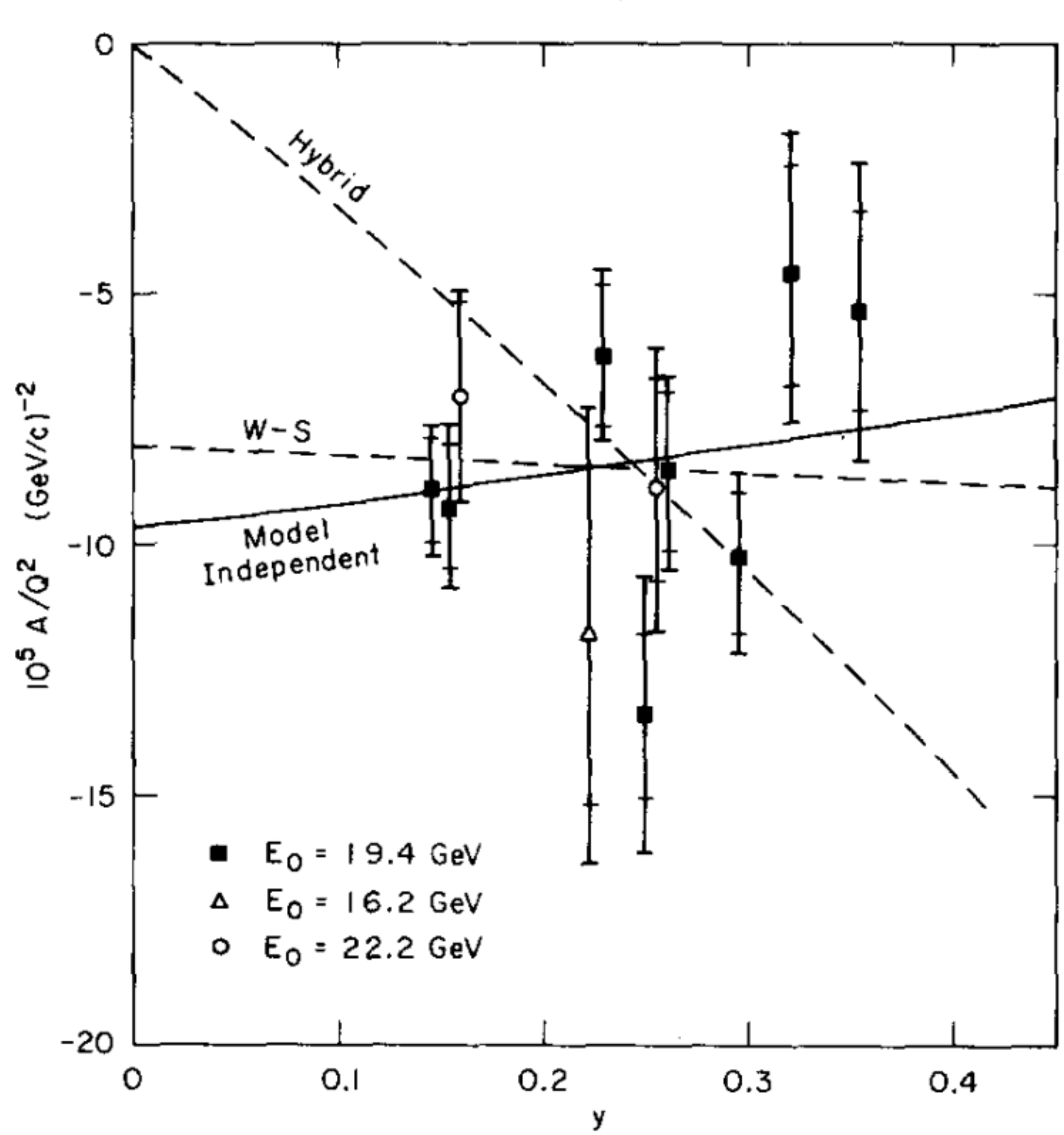
Table I. Experimentally studied N. C. processes.

Process	Comparison with theory
1. Purely leptonic	
$\nu_\mu+e^-\to\nu_\mu+e^-$	Very clean
$\bar{\nu}_\mu+e^-\to\bar{\nu}_\mu+e^-$	(No hadrons involved)
$\bar{\nu}_e+e^-\to\bar{\nu}_e+e^-$	
2. Elastic scattering	Relatively straightforward.
$\nu_\mu+p\to\nu_\mu+\pi$	Some uncertainty due to
$\bar{\nu}_\mu+p\to\bar{\nu}_\mu+\pi$	proton form factors (M_A).
3. Single pion production	Model dependent due to
$\nu_\mu+N\to\nu_\mu+N'+\pi$	hadronic vertex.
$\bar{\nu}_\mu+N\to\bar{\nu}_\mu+N'+\pi$	Also nuclear physics corr.
4. Inclusive	Quark-parton model
$\nu_\mu+N\to\nu_\mu+\ldots$	Dependent.
$\bar{\nu}_\mu+N\to\bar{\nu}_\mu+\ldots$	
5. Atomic physics	Large uncertainites due to
$e^-+Bi\to e^-+Bi$	atomic physics calculations.
6. Electron scattering	Quark–parton model
$\vec{e}^-+d\to e^-+\ldots$	dependent.



Baltay, Conf.Proc.C 780823 (1978) 882

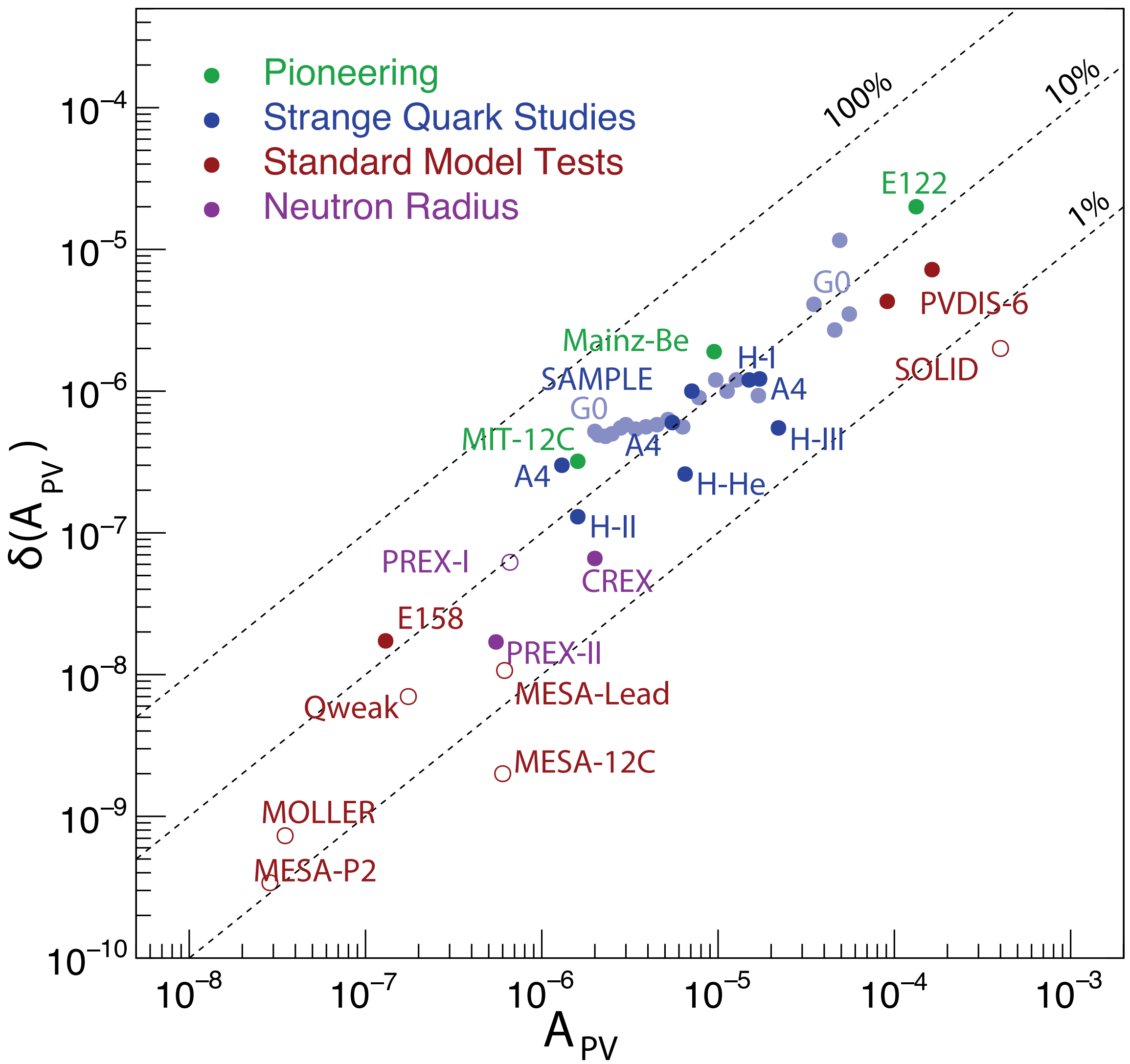
With increased statistics, the angular distribution of the asymmetry was able to rule out models



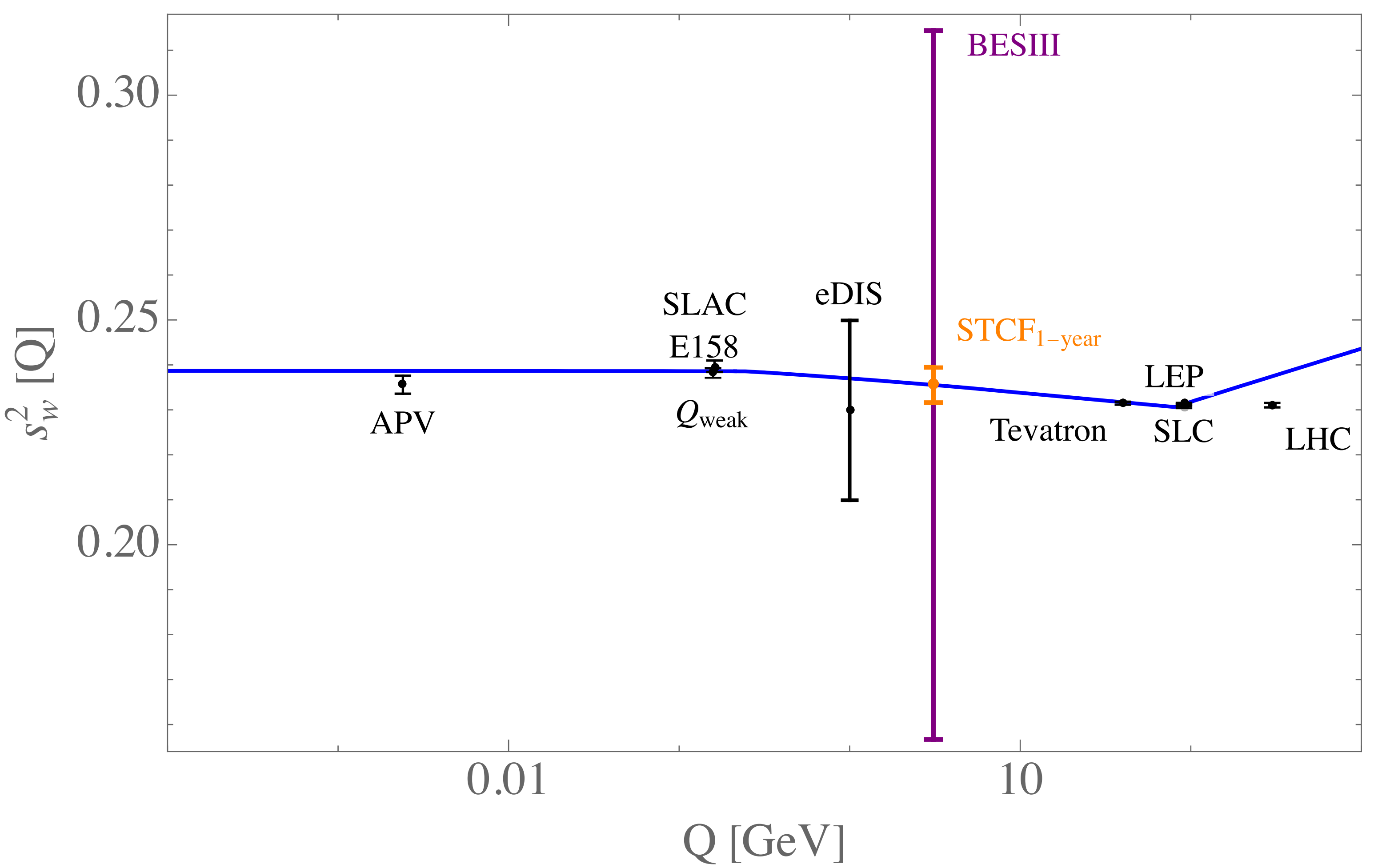
Prescott et al, PLB 77 (1978) 347, 84 (1979) 524

Introduction

The SM, as itself a chiral theory, has then been tested more and more precisely using the parity-violating asymmetry



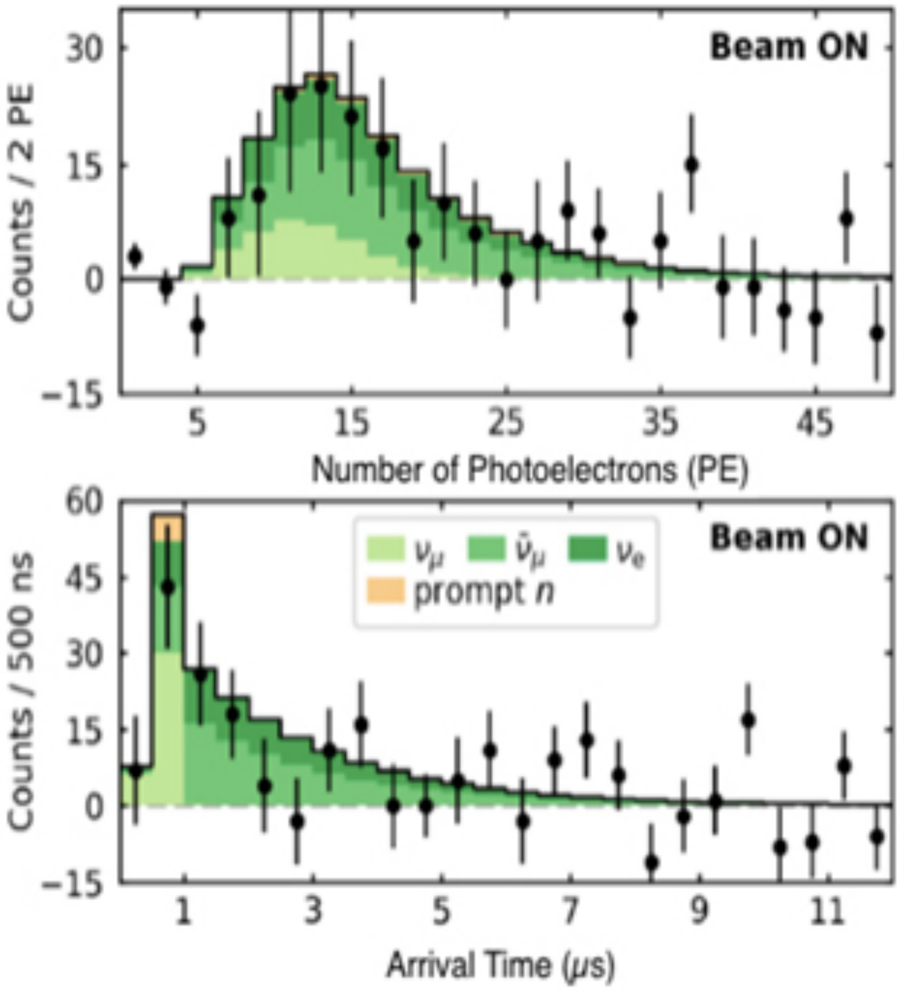
P2 collaboration, 1802.04759 (EPJA)



YD, He, Ma, Du, 2405.09625

Introduction

CEvNS, as firstly observed in 2017, is another type of experiment for neutral current detection with an N^2 enhancement from the target



COHERENT collaboration
Science 357 (2017)
PRL 126 (2021)

Introduction

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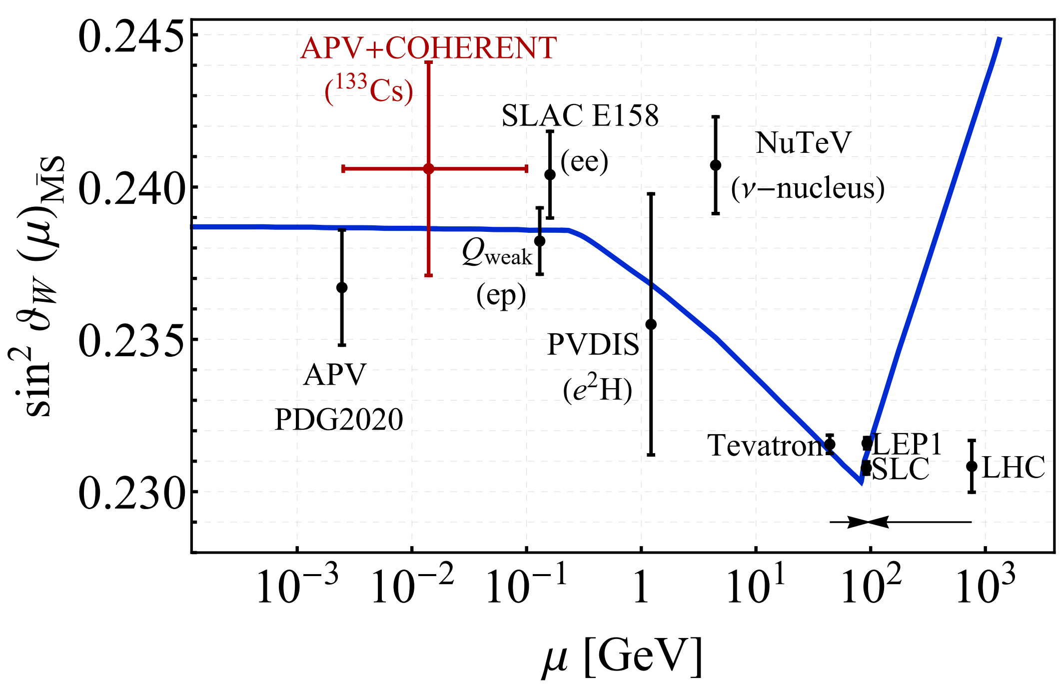
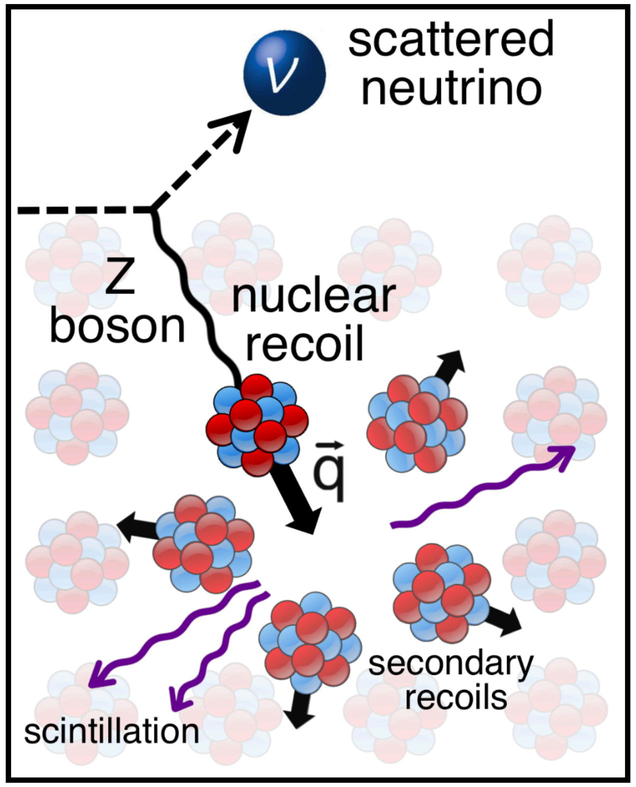
1. **Weak mixing angle determination**



M. Cadeddu et al, PRC 2021

2. **Model discriminator** ✓



+ many other interesting possibilities (nucleon/neutrino charge radii, dark matter, sterile neutrinos, neutrino magnetic moment, light mediators etc…) as we've heard in the morning

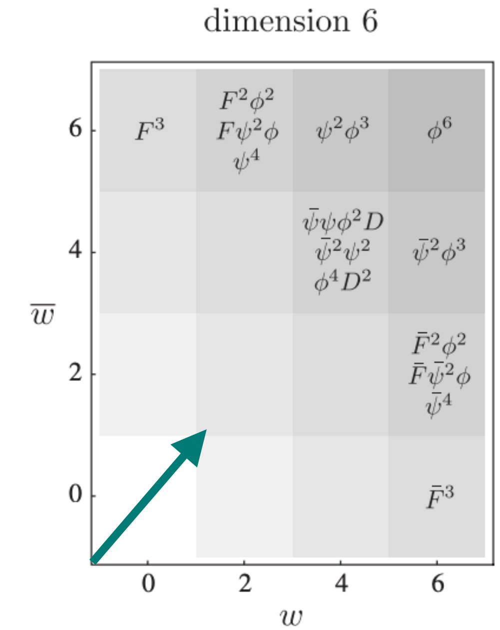
Formalism

The validity of the EFT approach is guaranteed by the small momentum transfer of CEvNS: $|Q| \lesssim 1/R \sim \mathcal{O}(10)\,\mathrm{MeV}$.

Cheung et al, PRL 115 071601 (2015)

$\omega \equiv n - h$

$\bar{\omega} \equiv n + h$



E

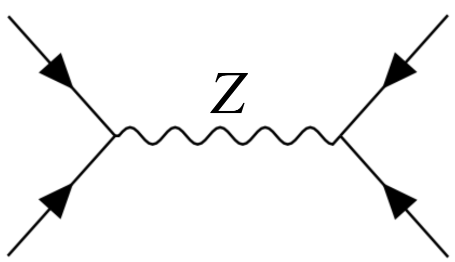
Λ — (Even more anomalous dimension induced ones)

$\mathcal{O}^{(1,3)}_{lq,Hl}(\mu = v_\Lambda)$ $\qquad$ $\mathcal{O}_{lu,ld}(\mu = v_\Lambda)$

RGE

Anomalous dimension induced

v_{EW}



$\mathcal{O}^{(1,3)}_{lq,Hl}(\mu = v_{\mathrm{EW}})$

RGE

CEvNS

$$\mathcal{L}_{\mathrm{NC}} \supset 2\sqrt{2}G_F\left[\epsilon^{fL}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_L f) + \epsilon^{fR}_{\alpha\beta}(\bar{\nu}_\alpha\gamma^\mu P_L\nu_\beta)(\bar{f}\gamma_\mu P_R f)\right] + \textbf{h.c.}$$

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$$\mathscr{L}_{\rm NC} \supset 2\sqrt{2}G_F\left[\epsilon^{fL}_{\alpha\beta}(\bar\nu_\alpha\gamma^\mu P_L\nu_\beta)(\bar f\gamma_\mu P_L f) + \epsilon^{fR}_{\alpha\beta}(\bar\nu_\alpha\gamma^\mu P_L\nu_\beta)(\bar f\gamma_\mu P_R f)\right] + \textbf{h.c.}$$

$$g_p^V = g_p^{V,\,\rm SM} + 3[c_{\ell q}] + [c^{(3)}_{\ell q}] + 2[c_{\ell u}] + [c_{\ell d}]$$

$$g_n^V = g_n^{V,\,\rm SM} + 3[c_{\ell q}] - [c^{(3)}_{\ell q}] + [c_{\ell u}] + 2[c_{\ell d}]$$

$$\mathcal{O}^{(1)}_{lq} = \left(\bar l_p\gamma^\mu l_r\right)\left(\bar l_s\gamma_\mu l_t\right)$$

$$\mathcal{O}^{(3)}_{lq} = \left(\bar l_p\gamma^\mu\tau^I l_r\right)\left(\bar l_s\gamma_\mu\tau^I l_t\right)$$

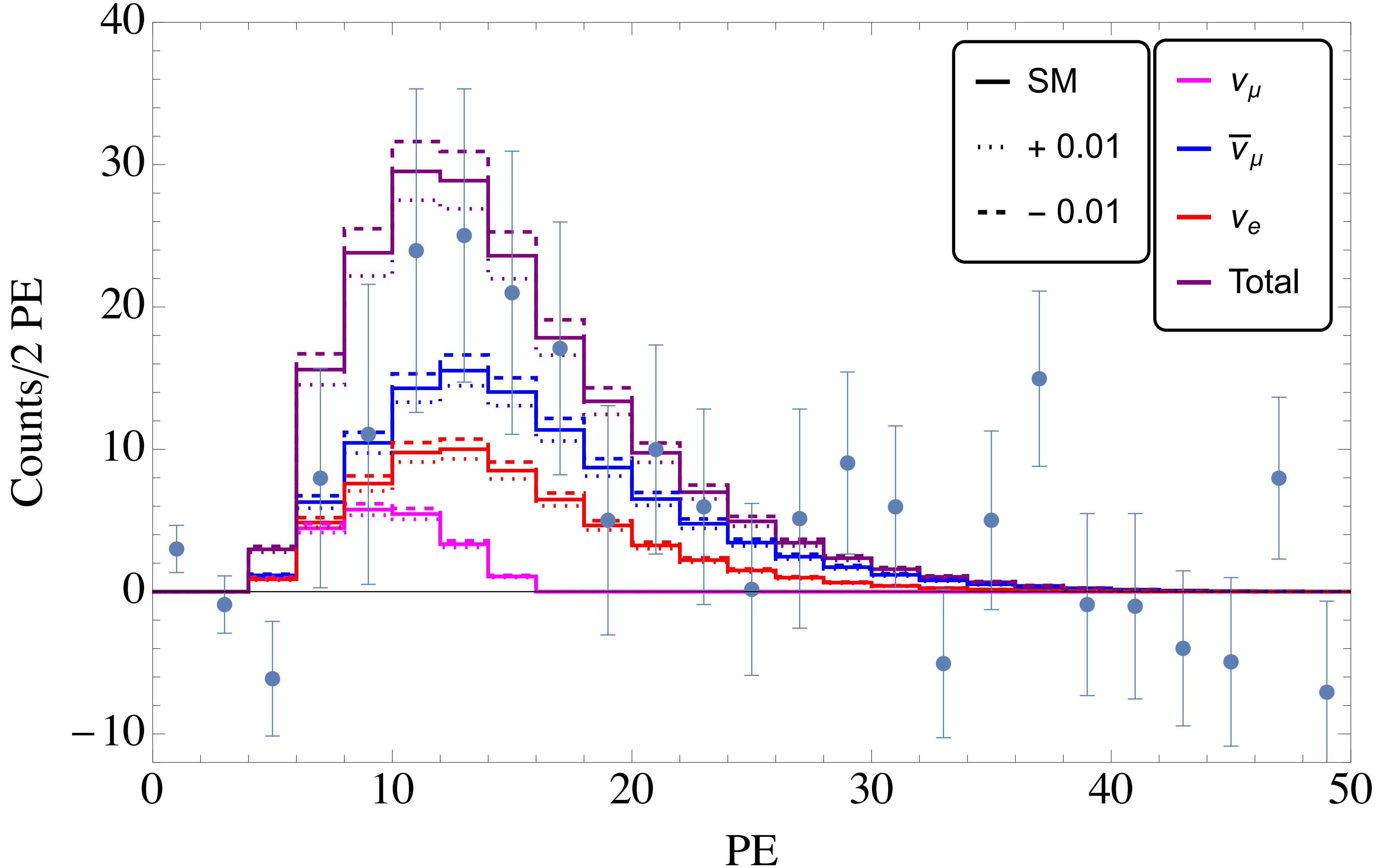
$$\mathcal{O}_{lQ} = \left(\bar l_p\gamma^\mu l_r\right)\left(\bar Q_s\gamma_\mu Q_t\right)$$

which then modifies the prediction for the number of events

$$\frac{d\sigma_\alpha^{\rm SMEFT}}{dE_r} \propto \left[N(-1 + 2\epsilon^{uV}_{\alpha\alpha} + 4\epsilon^{dV}_{\alpha\alpha}) + Z(1 - 4s_W^2 + 4\epsilon^{uV}_{\alpha\alpha} + 2\epsilon^{dV}_{\alpha\alpha})\right]^2$$

Results

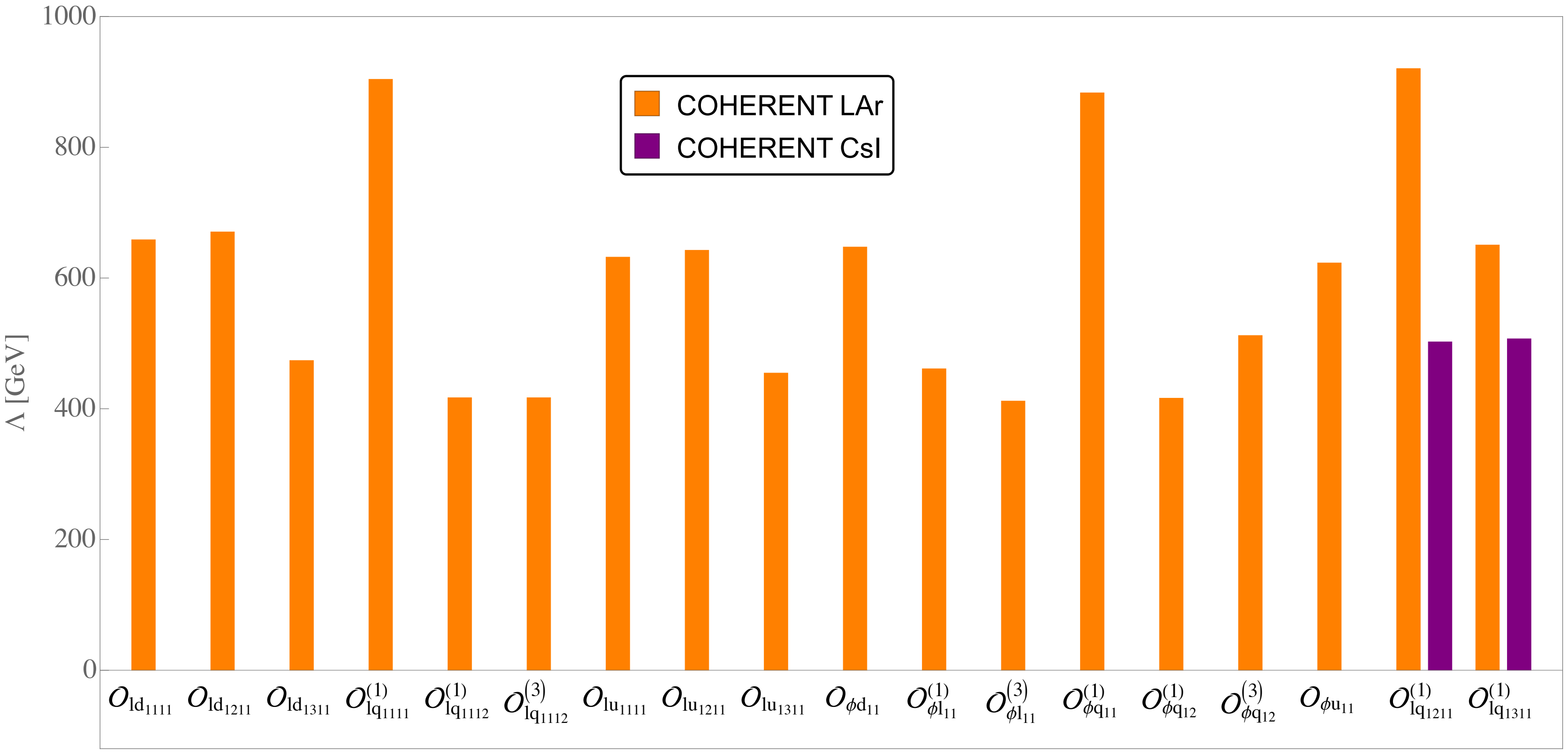
The magnitude of these Wilson coefficients can not be arbitrarily large



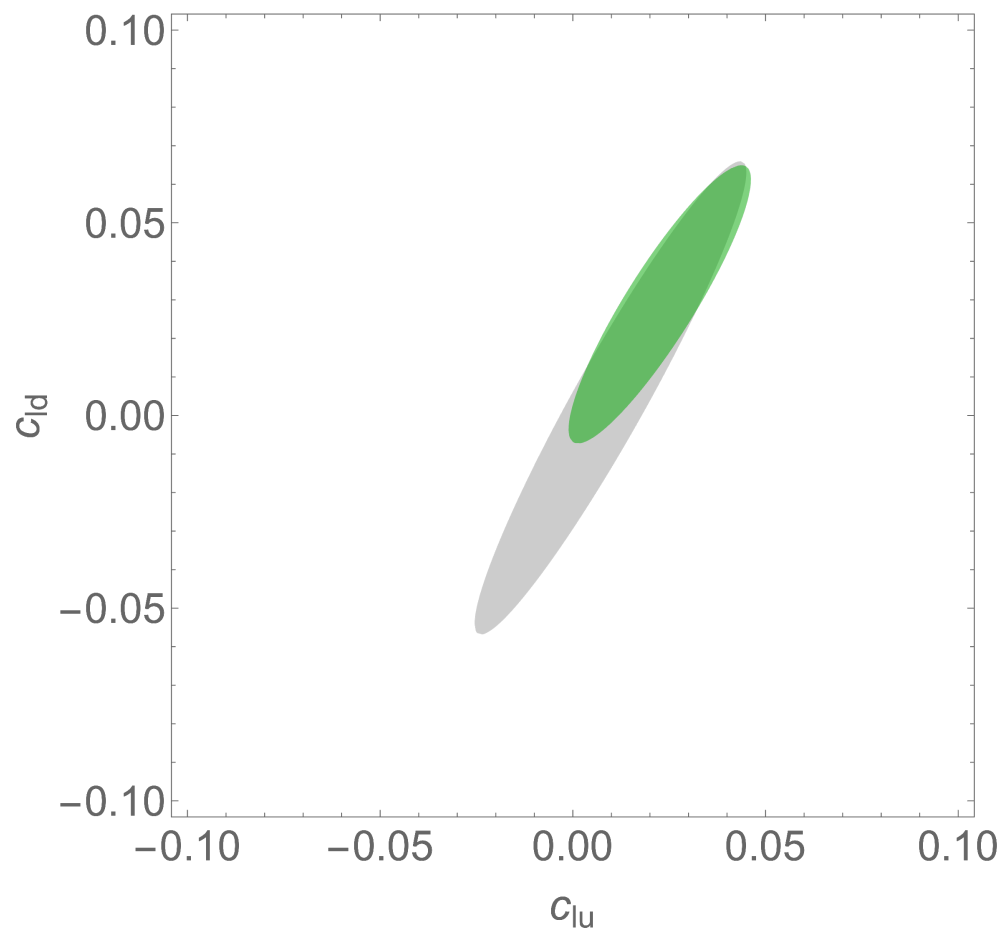
COHERENT collaboration
Science 357 (2017)

Results

Considering one operator at a time



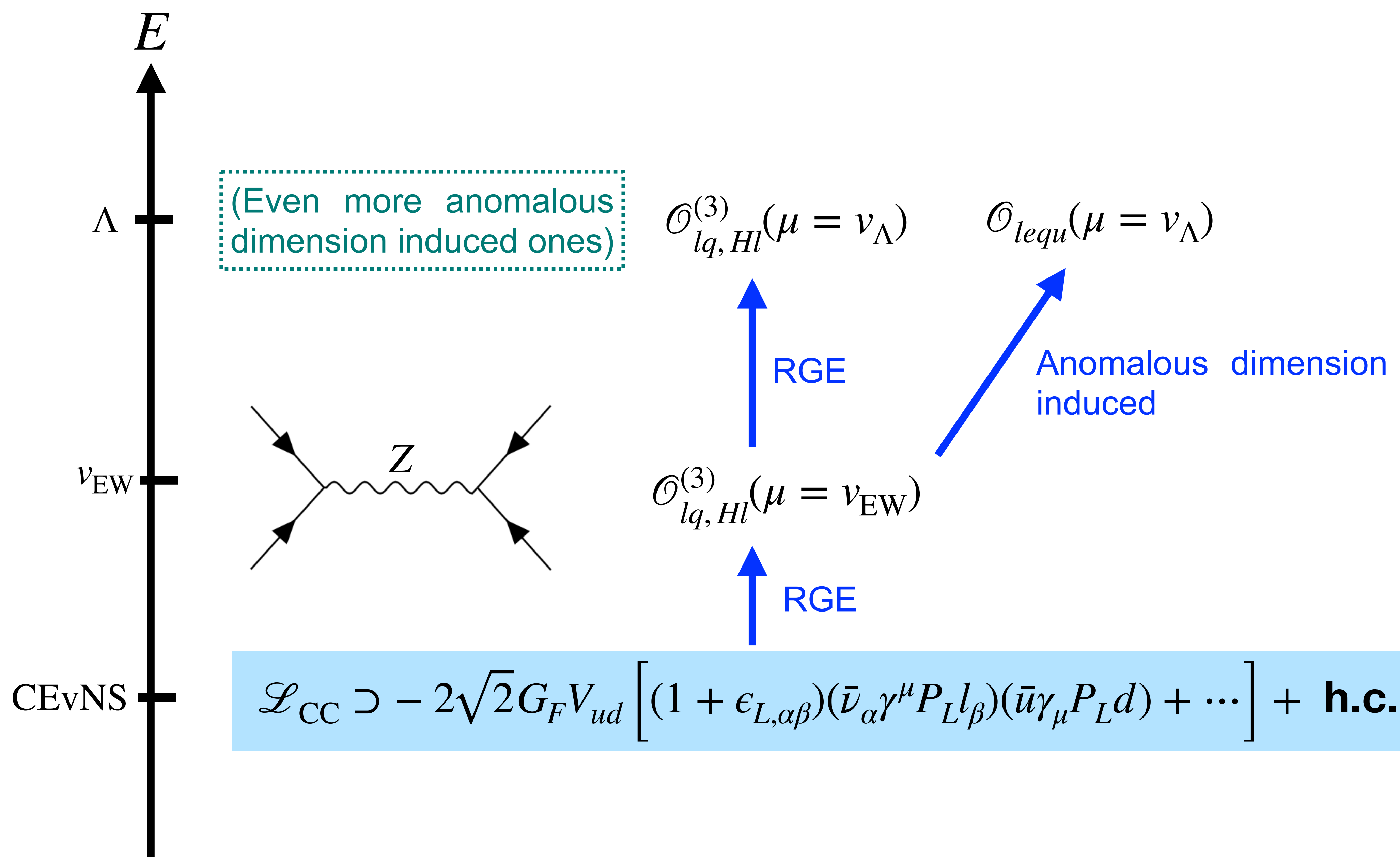
YD, Li, Tang, Vihonen, Yu, arXiv: 2106.15800



Breso-Pla, Falkowski, Gonzalez-Alonso, Monsalvez-Pozo, 2301.07036 (JHEP)

Charged-Current NSIs

The same logic applies to neutrino oscillations where charged-current processes are also present.



$$\mathscr{L}_{\rm CC} \supset -2\sqrt{2}G_F V_{ud}\left[(1+\epsilon_{L,\alpha\beta})(\bar{\nu}_\alpha\gamma^\mu P_L l_\beta)(\bar{u}\gamma_\mu P_L d)+\cdots\right] + \textbf{h.c.}$$

Charged-Current NSIs

A combined analysis of neutral and charged currents is thus possible, where we can include both CEvNS data and neutrino oscillation data with one caveat

$$|\nu_\alpha^s\rangle = \frac{(1+\epsilon^s)_{\alpha\gamma}}{N_\alpha^s}|\nu_\gamma\rangle, \ \langle\nu_\beta^d| = \langle\nu_\gamma|\frac{(1+\epsilon^d)_{\gamma\beta}}{N_\beta^d}$$

in terms of wavepacket deformation

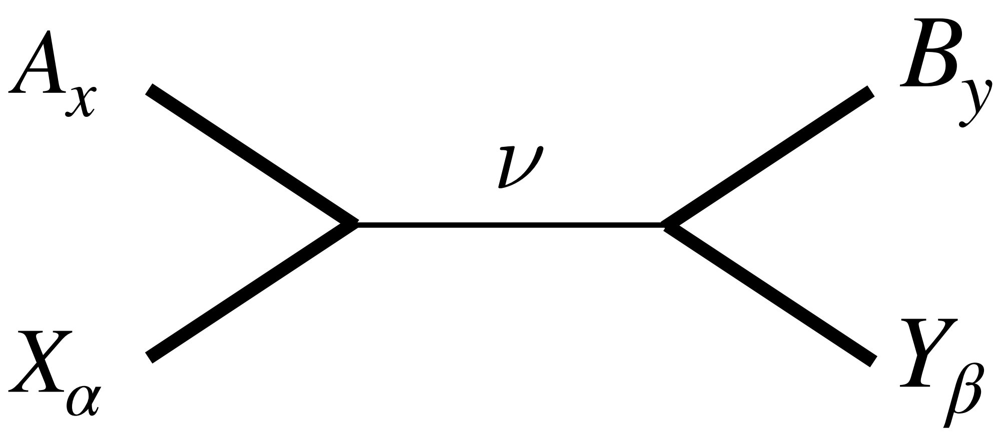
$$\begin{aligned}\mathscr{L}_{\rm CC} = -\frac{2V_{ud}}{v^2}\{ & \left[1+\epsilon_L\right]_{\alpha\beta}(\bar{u}\gamma^\mu P_L d)\left(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta\right) + \left[\epsilon_R\right]_{\alpha\beta}(\bar{u}\gamma^\mu P_R d)\left(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta\right) \\ & +\frac{1}{2}\left[\epsilon_S\right]_{\alpha\beta}(\bar{u}d)\left(\bar{\ell}_\alpha P_L\nu_\beta\right) - \frac{1}{2}\left[\epsilon_P\right]_{\alpha\beta}(\bar{u}\gamma_5 d)\left(\bar{\ell}_\alpha P_L\nu_\beta\right) \\ & +\frac{1}{4}\left[\epsilon_T\right]_{\alpha\beta}(\bar{u}\sigma^{\mu\nu}P_L d)\left(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta\right) + \textbf{h.c.} \ \}\end{aligned}$$

A consistent matching between the quantum mechanical and the quantum field theory formalisms.

Charged-Current NSIs

This is achieved by matching at the observable level (i.e., the differential event rate)

$$A_x \to X_\alpha \nu, \quad \nu B_y \to Y_\beta$$



$$R^{\rm QM}_{\alpha\beta} = \Phi^{\rm SM}_\alpha \sigma^{\rm SM}_\beta \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} [x_s]_{\alpha k}[x_s]^*_{\alpha l}[x_d]_{\beta k}[x_d]^*_{\beta l}$$

$$R^{\rm QFT}_{\alpha\beta} = \frac{N_S}{32\pi L^2 m_S m_T E_\nu} \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} \int d\Pi_{P'} \mathcal{M}^P_{\alpha k} \bar{\mathcal{M}}^P_{\alpha l} \int d\Pi_D \mathcal{M}^D_{\beta k} \bar{\mathcal{M}}^D_{\beta l}$$

Falkowski, Gonzalez-Alonso, Tabrizi, 1910.02971 (JHEP)

New Physics effects included from both the production and the detection sides.

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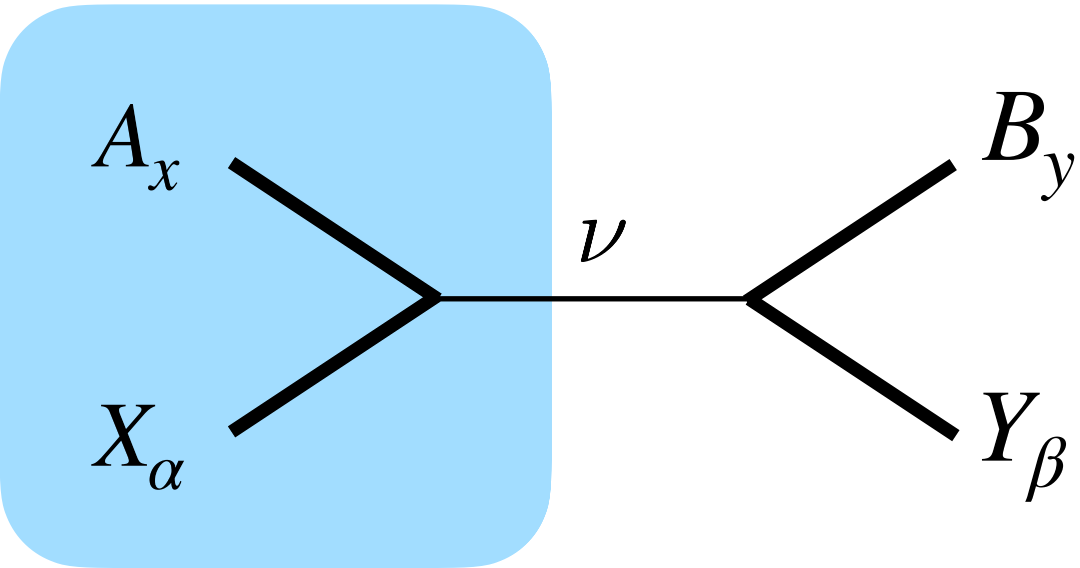

$$R^{\text{QM}}_{\alpha\beta} = \Phi^{\text{SM}}_\alpha \sigma^{\text{SM}}_\beta \sum_{k,l} e^{-i\frac{L\Delta m^2_{kl}}{2E_\nu}} [x_s]_{\alpha k}[x_s]^*_{\alpha l}[x_d]_{\beta k}[x_d]^*_{\beta l}$$

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$$\mathcal{M}^P_{\alpha k} = U^*_{\alpha k} A^P_L + \sum_X \left[\epsilon_X U\right]^*_{\alpha k} A^P_X$$

Falkowski, Gonzalez-Alonso, Tabrizi, 1910.02971 (JHEP)

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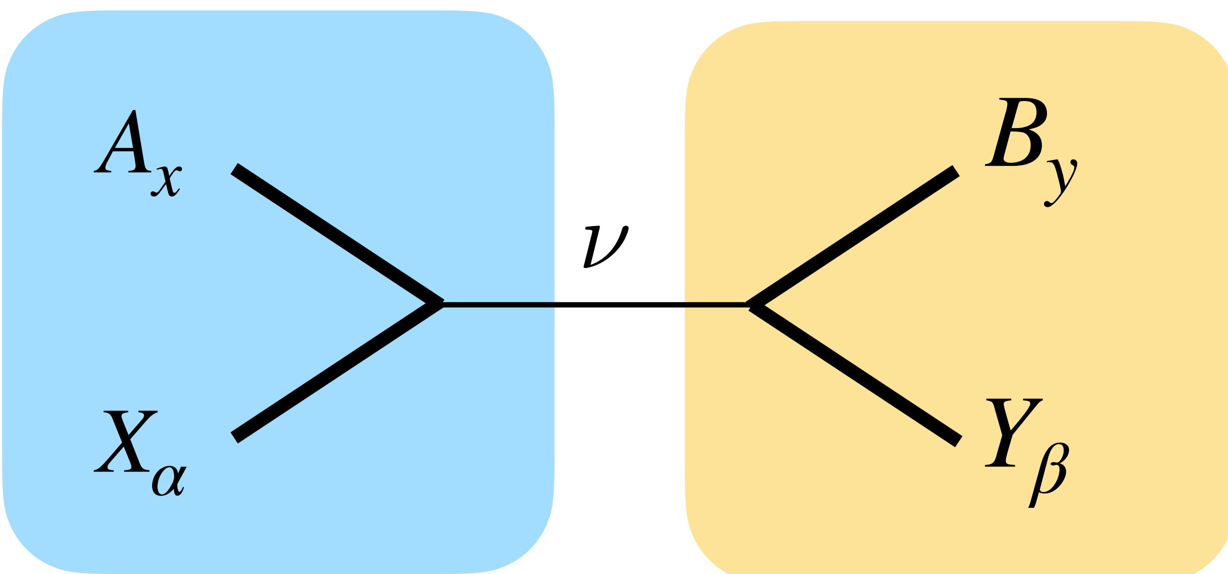

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$$\mathcal{M}^P_{\alpha k} = U^*_{\alpha k} A^P_L + \sum_X \left[\epsilon_X U\right]^*_{\alpha k} A^P_X$$

$$\mathcal{M}^D_{\beta k} = U_{\beta k} A^D_L + \sum_X \left[\epsilon_X U\right]_{\beta k} A^D_X$$

Falkowski, Gonzalez-Alonso, Tabrizi, 1910.02971 (JHEP)

New Physics effects included from both the production and the detection sides.

Charged-Current NSIs

QM NSIs	Relations to QFT NSIs
$\epsilon^s_{e\beta}$ (β decay)	$\left[\epsilon_L - \epsilon_R - \frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}\epsilon_T\right]^*_{e\beta}$
$\epsilon^d_{\beta e}$ (inverse β decay)	$\left[\epsilon_L + \frac{1-3g_A^2}{1+3g_A^2}\epsilon_R - \frac{m_e}{E_\nu-\Delta}\left(\frac{g_S}{1+3g_A^2}\epsilon_S - \frac{3g_A g_T}{1+3g_A^2}\epsilon_T\right)\right]_{e\beta}$
$\epsilon^s_{\mu\beta}$ (pion decay)	$\left[\epsilon_L - \epsilon_R - \frac{m_\pi^2}{m_\mu(m_u+m_d)}\epsilon_P\right]^*_{\mu\beta}$
$\epsilon^s_{\mu\beta}$ (muon decay)	$\left[g_{22} + \frac{3m_e m_\mu(m_\mu-2E_\nu)}{16m_\mu E_\nu^2+6m_\mu(m_\mu^2+m_e^2)-4E_\nu(5m_\mu^2+m_e^2)}h_{21}\right]^*_{\mu\beta}$
$\epsilon^s_{e\beta}$ (muon decay)	$\left[g_{22} + \frac{m_e}{4(m_\mu-2E_{\bar\nu})}h_{21}\right]^*_{e\beta}$

$$\mathscr{L}_{e\mu} = \frac{G_F}{\sqrt{2}}\left\{g_{22}\left(\bar{e}_L\gamma^\mu\nu_{eL}\right)\left(\bar{\nu}_{\mu L}\gamma_\mu\mu_L\right) - 2h_{21}\left(\bar{\nu}_{eL}e_R\right)\left(\bar{\mu}_R\nu_{\mu L}\right) + \text{H.c.}\right\}.$$

Falkowski, Gonzalez-Alonso, Tabrizi, 1910.02971 (JHEP)

YD, Li, Tang, Vihonen, Yu, 2011.14292(JHEP)

Charged-Current NSIs

Matter effects matter especially for long-baseline neutrino oscillation experiments from the neutral current

$$A = \sqrt{2} G_F N_e$$

$$H = \frac{1}{2E_\nu}\left[U\begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{21}^2 & 0 \\ 0 & 0 & \Delta m_{31}^2 \end{pmatrix}U^\dagger + A\begin{pmatrix} 1+\varepsilon_{ee}^m & \epsilon_{e\mu}^m & \epsilon_{e\tau}^m \\ \epsilon_{e\mu}^{m*} & \epsilon_{\mu\mu}^m & \epsilon_{\mu\tau}^m \\ \epsilon_{e\tau}^{m*} & \epsilon_{\mu\tau}^{m*} & \epsilon_{\tau\tau}^m \end{pmatrix}\right],$$

and the matching is straightforward

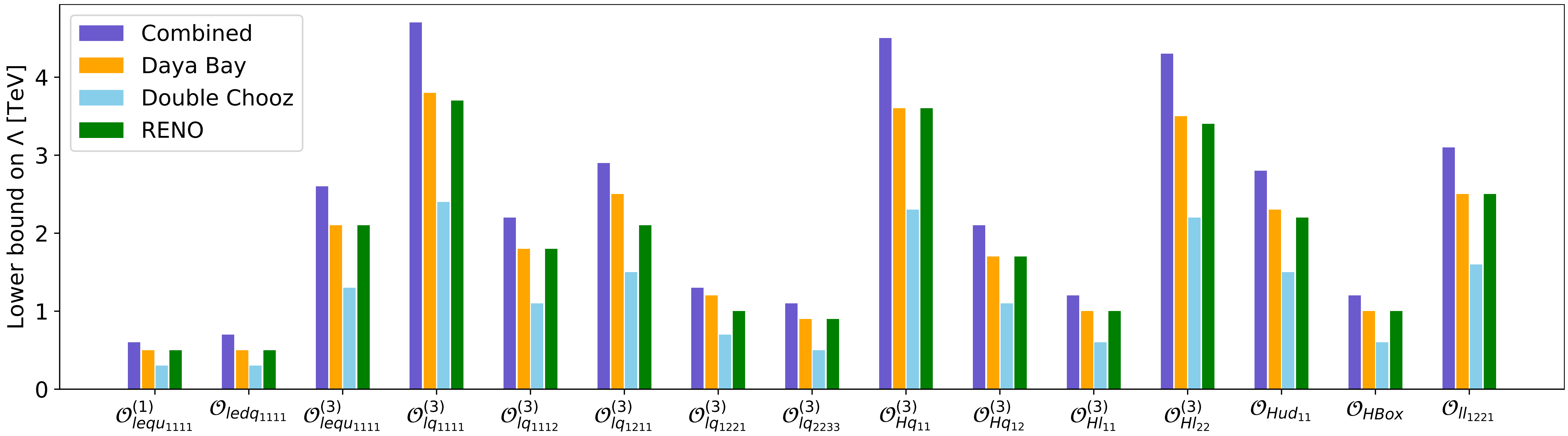
$$\mathscr{L}_{\rm NC} \supset 2\sqrt{2} G_F \left[\epsilon_{\alpha\beta}^{fL}(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_L f) + \epsilon_{\alpha\beta}^{fR}(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta)(\bar{f}\gamma_\mu P_R f)\right] + \textbf{h.c.} + X$$

X: Other Lorentz structures which however do not contribute to matter effects.

$$\epsilon_{\alpha\beta}^m = \sum_f \left\langle \frac{N_f(x)}{N_e(x)} \right\rangle (\epsilon_{\alpha\beta}^{fL} + \epsilon_{\alpha\beta}^{fR})$$

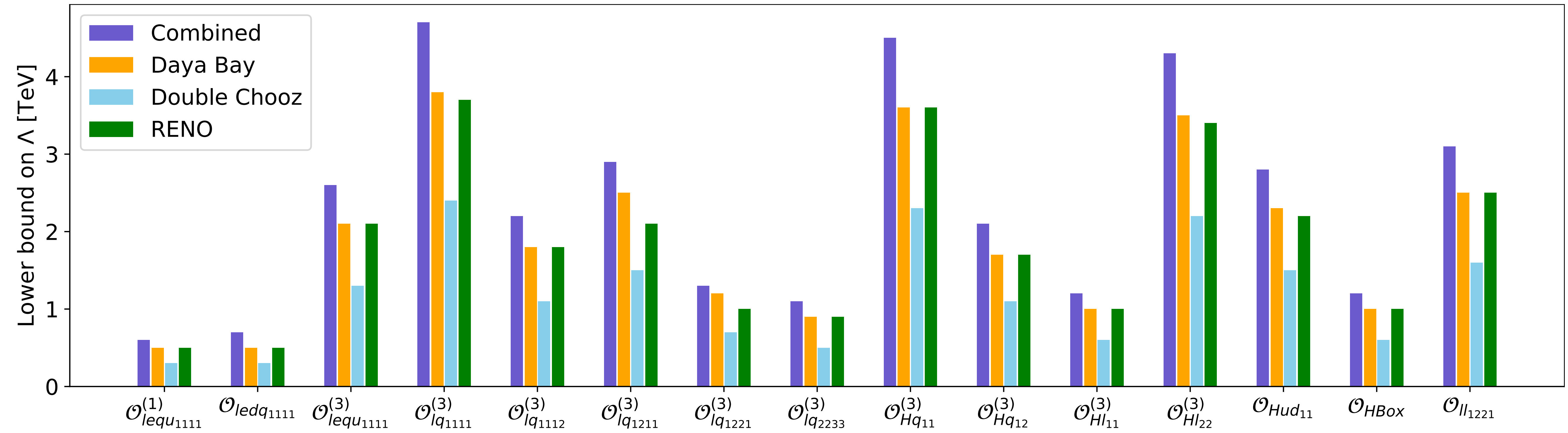
YD, Li, Tang, Vihonen, Yu, 2106.15800 (PRD)

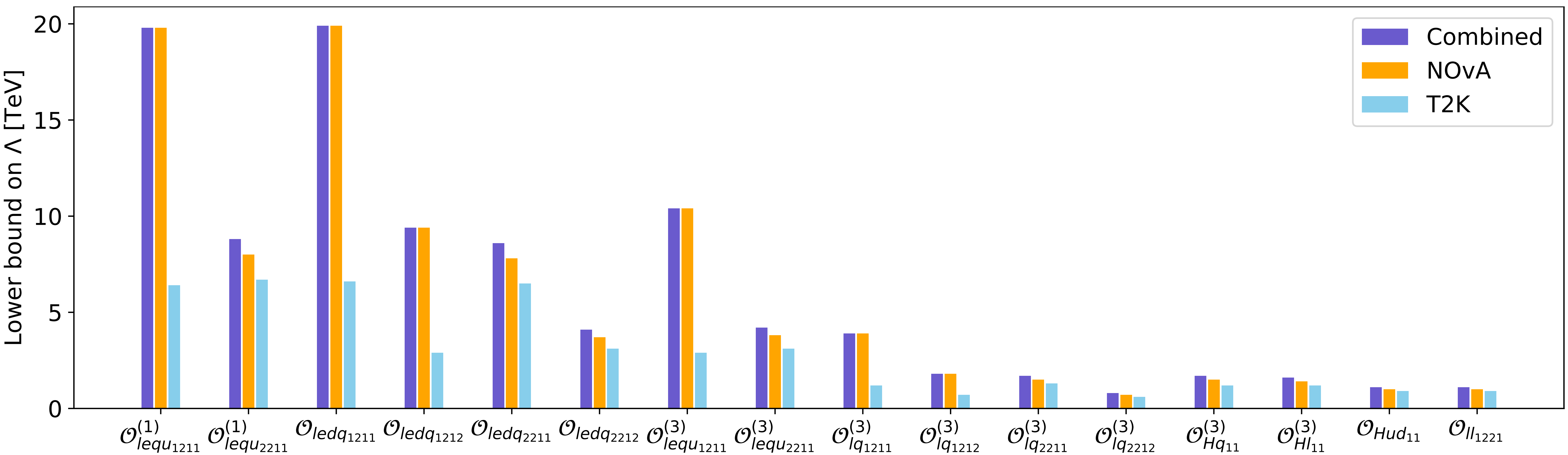
Charged-Current NSIs



YD, Li, Tang, Vihonen, Yu, 2011.14292 (JHEP)

Charged-Current NSIs





YD, Li, Tang, Vihonen, Yu, 2011.14292 (JHEP)

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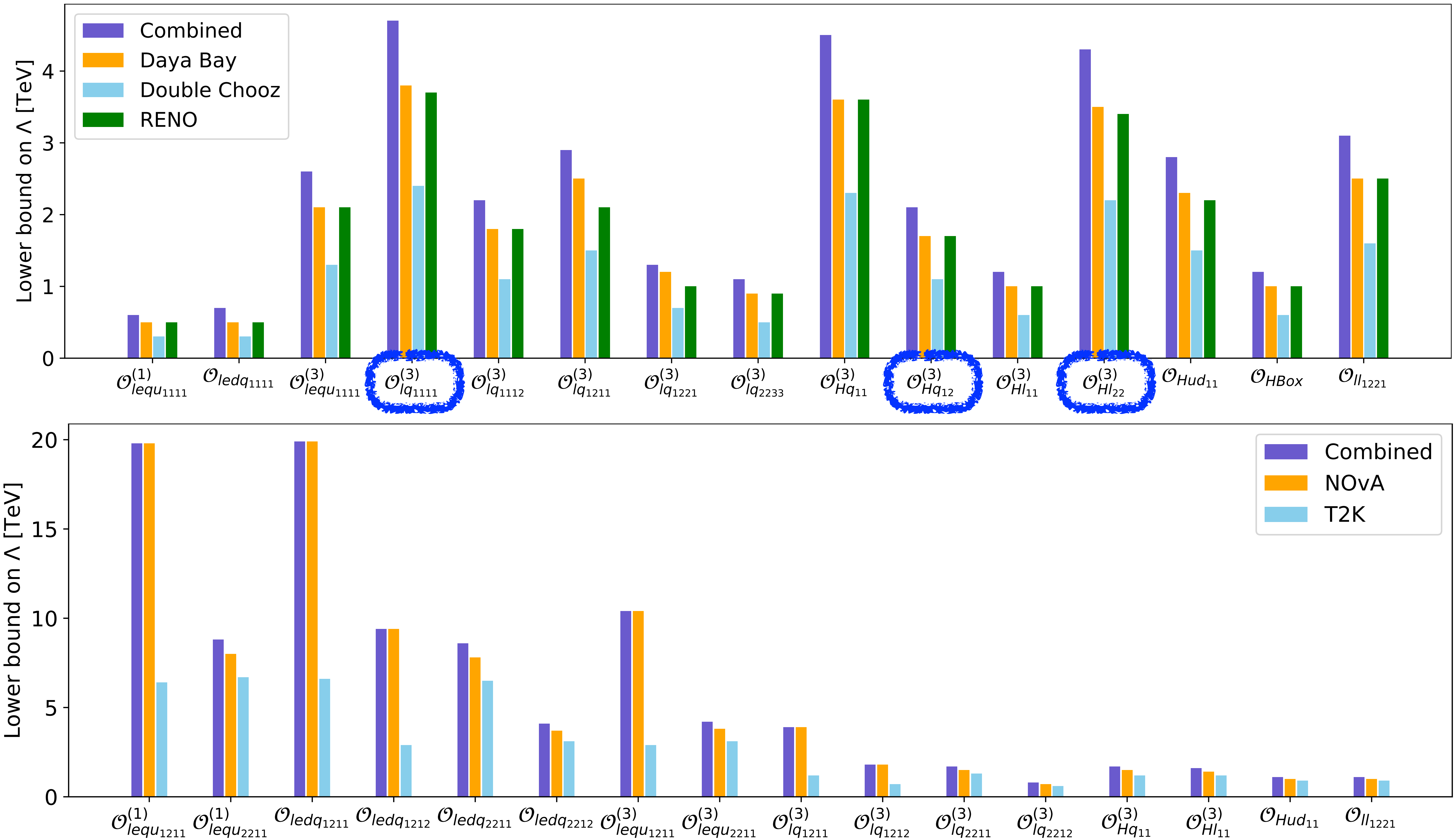

YD, Li, Tang, Vihonen, Yu, 2011.14292 (JHEP)

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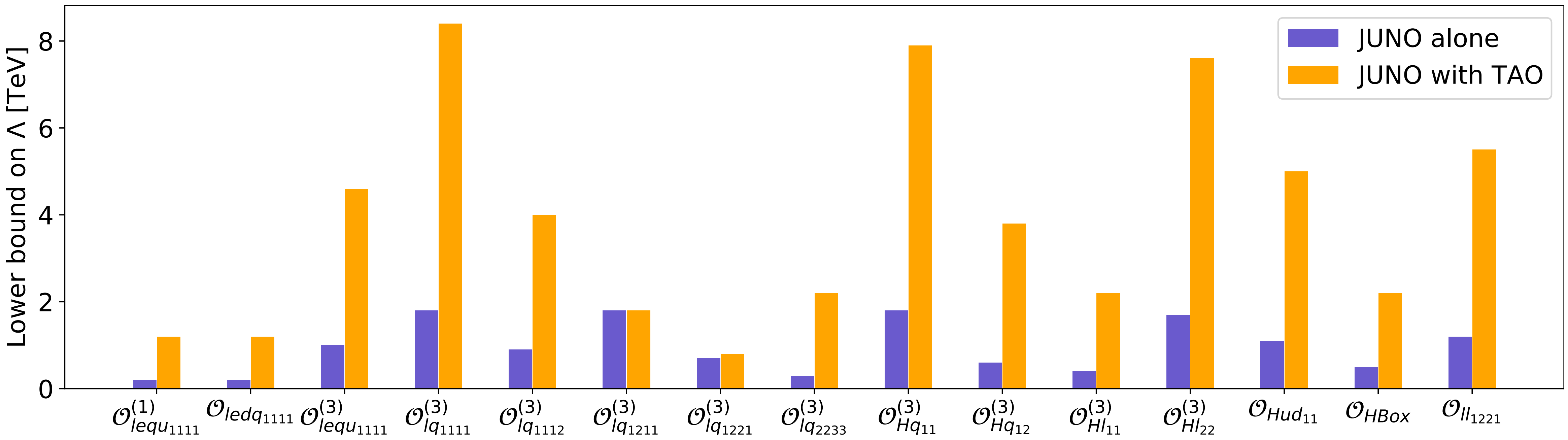
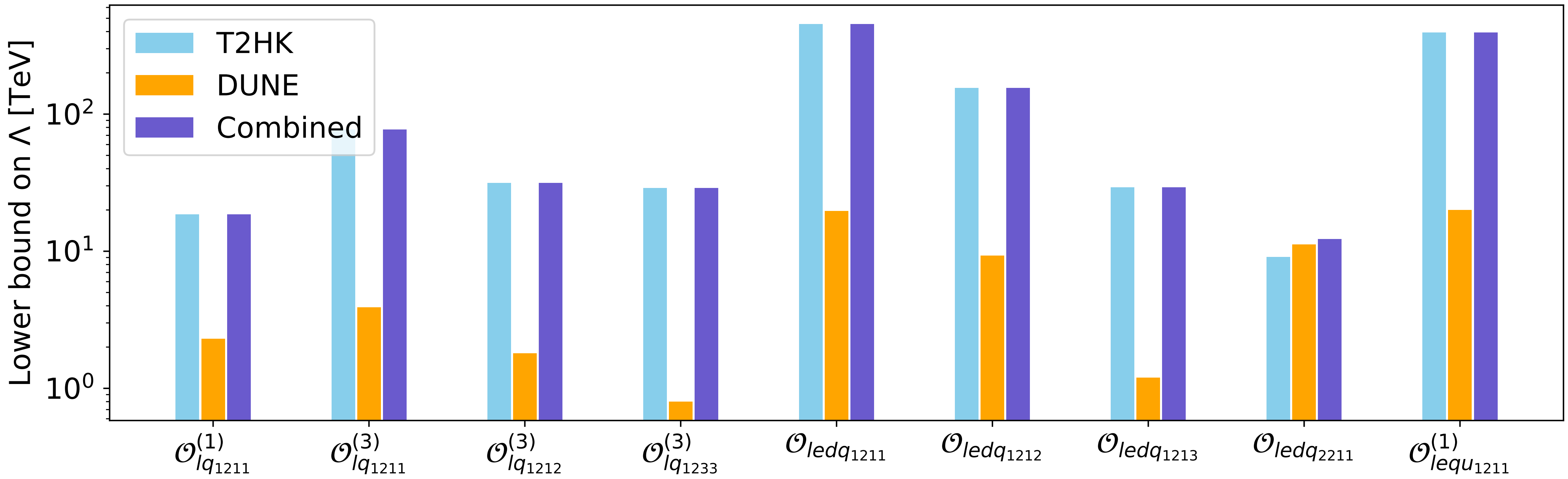




2106.15800, **YD**, H. Li, J. Tang, S. Vihonen, J-H Yu

Summary

- CEvNS could be a potential probe to discriminate models in the EFT framework. The current lower bounds on dim-6 operators are approaching the TeV scale new physics, a global analysis, with electroweak and 4-fermion data for instance, could be done in the precision CEvNS era with more data.

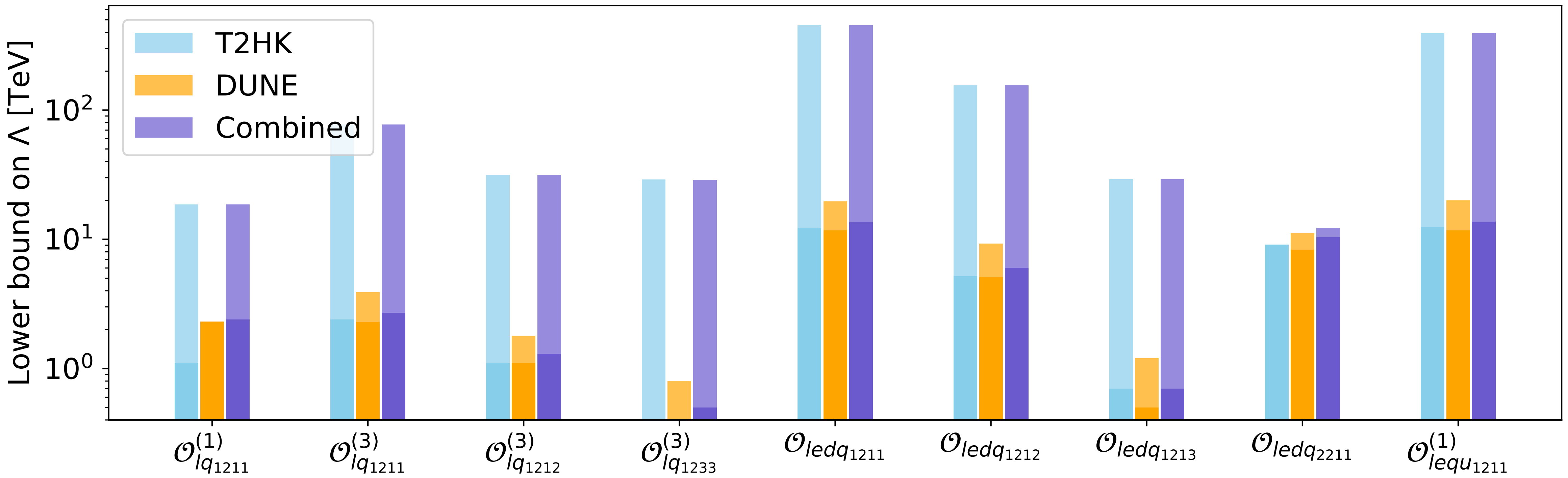
- Operators not directly contributing to CEvNS could also be explored through mixing from the anomalous dimension (currently around 500GeV as the lower bounds for those induced operators), especially given large logs resulted from the cutoff scale Λ and the CEvNs scale.

- CEvNS is also a complementary probe compared with neutrino oscillation experiments, and a combined analysis would be desirable given we will know the mass ordering in near future.

Backup

Charged-Current

Electron neutrino appearance is important in probing $\epsilon_{\mu e}^{s}$



2106.15800, **YD**, H. Li, J. Tang, S. Vihonen, J-H Yu