

Exploring non-standard neutrino interactions in SMEFT with laboratory experiments

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This work was done in collaboration with
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The results presented here are based on
arXiv:2011.14292 and arXiv:2106.15800



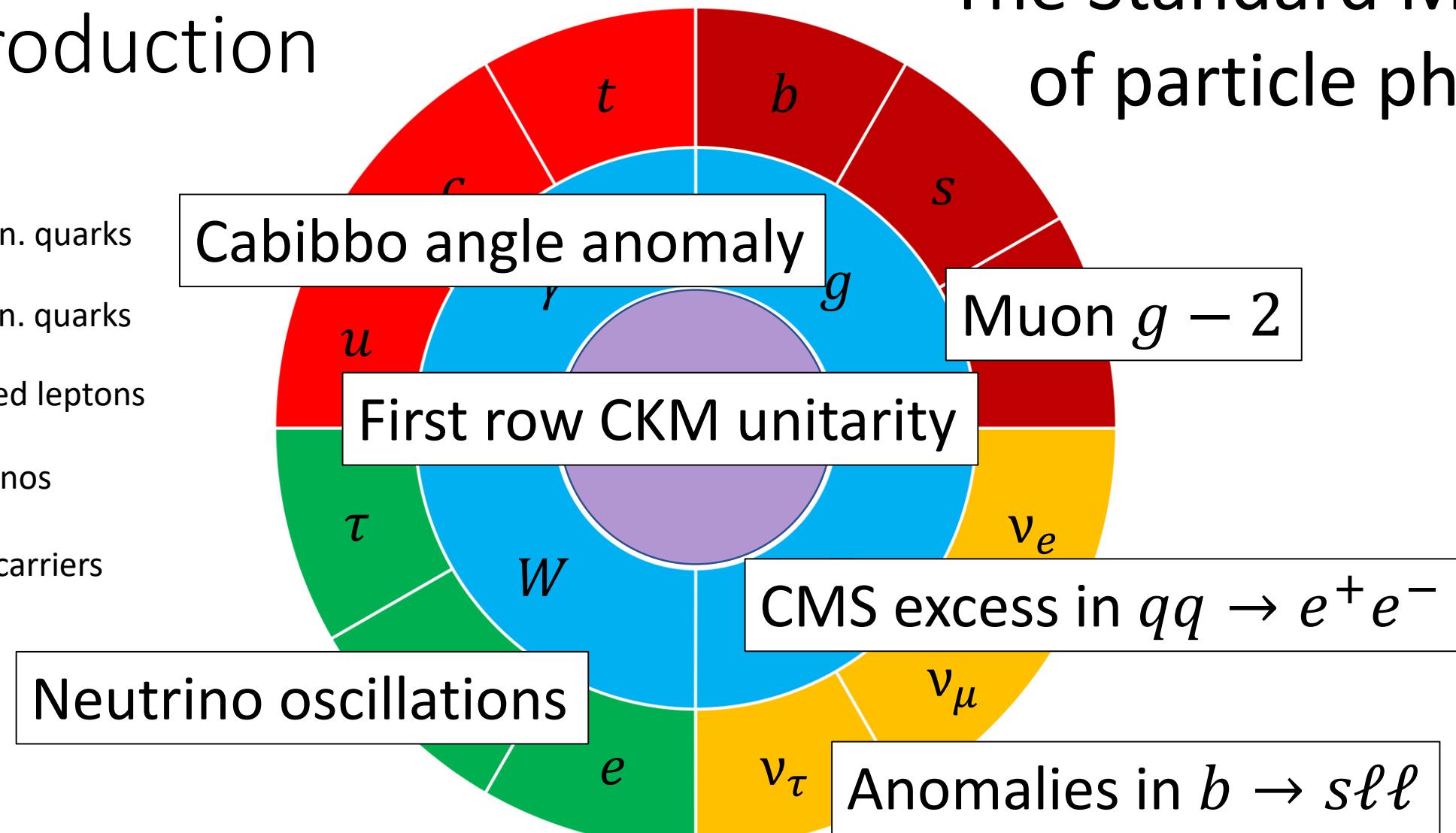
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The Standard Model of particle physics

Introduction

- 1st gen. quarks
- 2nd gen. quarks
- charged leptons
- neutrinos
- force carriers
- Higgs



Introduction

Neutrino oscillation data successfully explained
by three-neutrino mixing:

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric mixing

reactor mixing

solar mixing

ONLY SIX PARAMETERS: $\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}, \Delta m_{21}^2, \Delta m_{31}^2$

CKM matrix: ~few %
PMNS matrix: < 23 %

Introduction

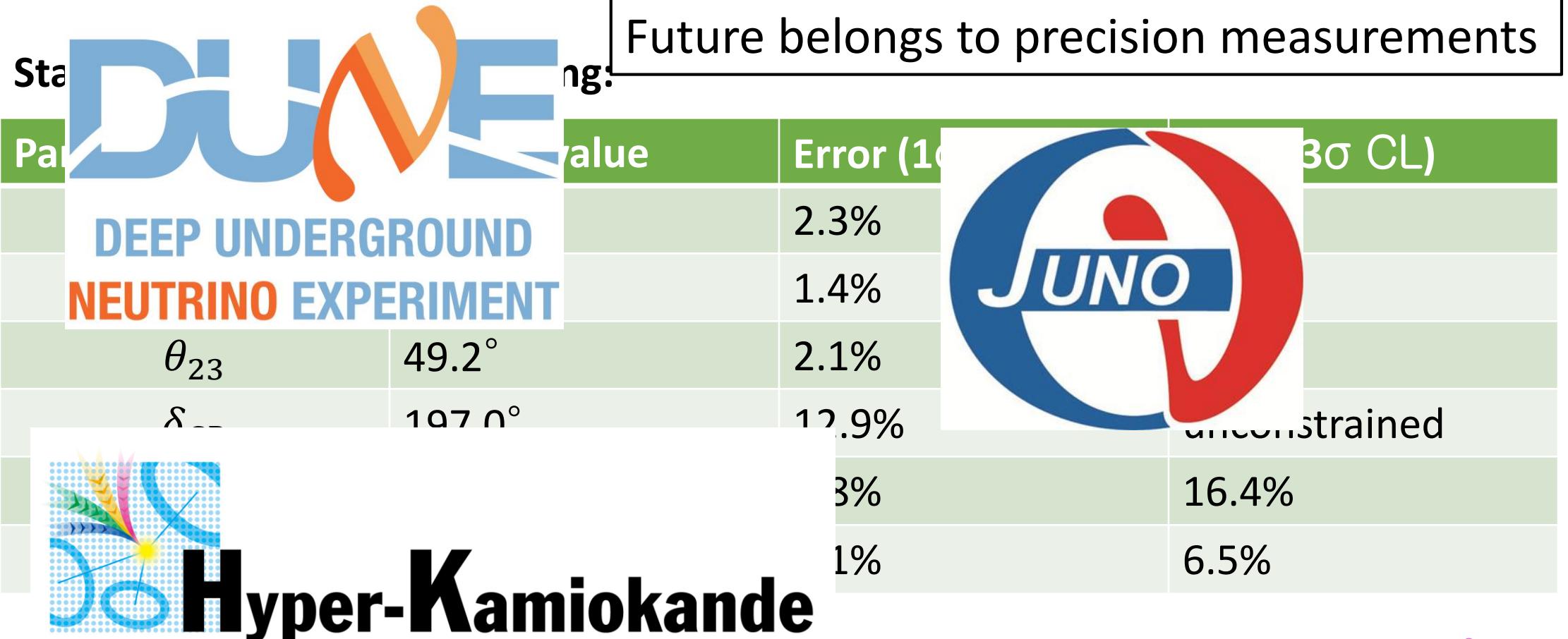
Status of three-neutrino mixing:

Parameter	Central value	Error (1σ CL)	Error (3σ CL)
θ_{12}	33.4°	2.3%	13.7%
θ_{13}	8.6°	1.4%	8.5%
θ_{23}	49.2°	2.1%	25.3%
δ_{CP}	197.0°	12.9%	unconstrained
Δm_{21}^2	$7.4 \times 10^{-5} \text{ eV}^2$	2.8%	16.4%
Δm_{31}^2	$2.5 \times 10^{-3} \text{ eV}^2$	1.1%	6.5%

NO, with SK atmospheric data

NuFIT group: www.nu-fit.org

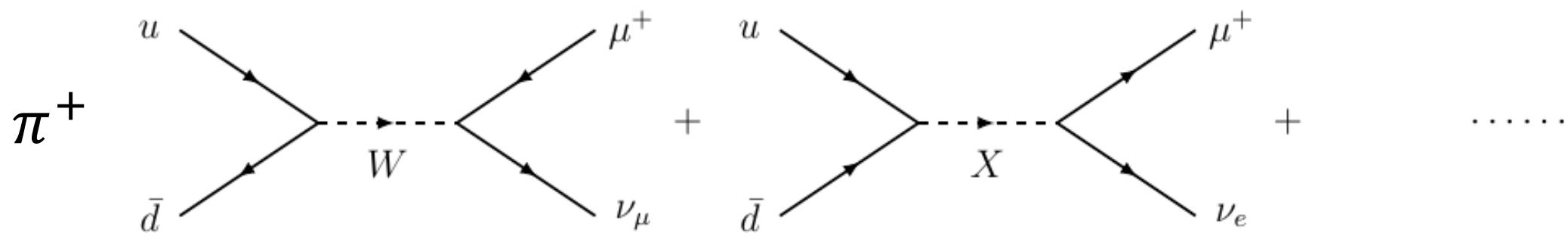
Introduction



Searching new physics in neutrino sector

There is still room for New Physics in neutrino oscillations

Example: source NSI in pion decay



Effective field theory approach

$$\mathcal{L}_{\text{CC}}^{\text{NSI}} = -2\sqrt{2}G_F \varepsilon_{\alpha\beta}^{ff',C} (\bar{v}_\alpha \gamma^\mu P_L \ell_\beta) (\bar{f} \gamma^\mu P_C f')$$

$$\varepsilon_{\mu e}^s = \varepsilon_{\mu e}^{ud} \propto \left(\frac{M_W}{M_X}\right)^2$$

Searching new physics in neutrino sector

Novel interactions in neutrino source, detector and propagation:

CC-like NSI: $\mathcal{L}_{\text{CC}}^{\text{NSI}} = -2\sqrt{2} G_F \epsilon_{\alpha\beta}^{ff',C} (\bar{v}_\alpha \gamma^\mu P_L l_\beta) (\bar{f} \gamma^\mu P_C f')$ *Production
Detection*

NC-like NSI: $\mathcal{L}_{\text{NC}}^{\text{NSI}} = -2\sqrt{2} G_F \epsilon_{\alpha\beta}^{fP} (\bar{v}_\alpha \gamma^\mu P_L v_\beta) (\bar{f} \gamma_\mu f)$ *Propagation*

BUT! Non-renormalizable, difficult to compare with other experimental findings....

Interpreting neutrino NSI in SMEFT

Standard Model Effective Field Theory: Powerful tool to study non-standard interactions in a universal framework.

$$\mathcal{L}_{\text{SMEFT}} = \sum_D \sum_{i_D} \frac{c_{i_D}}{\Lambda^{D-4}} \mathcal{O}_i^D$$

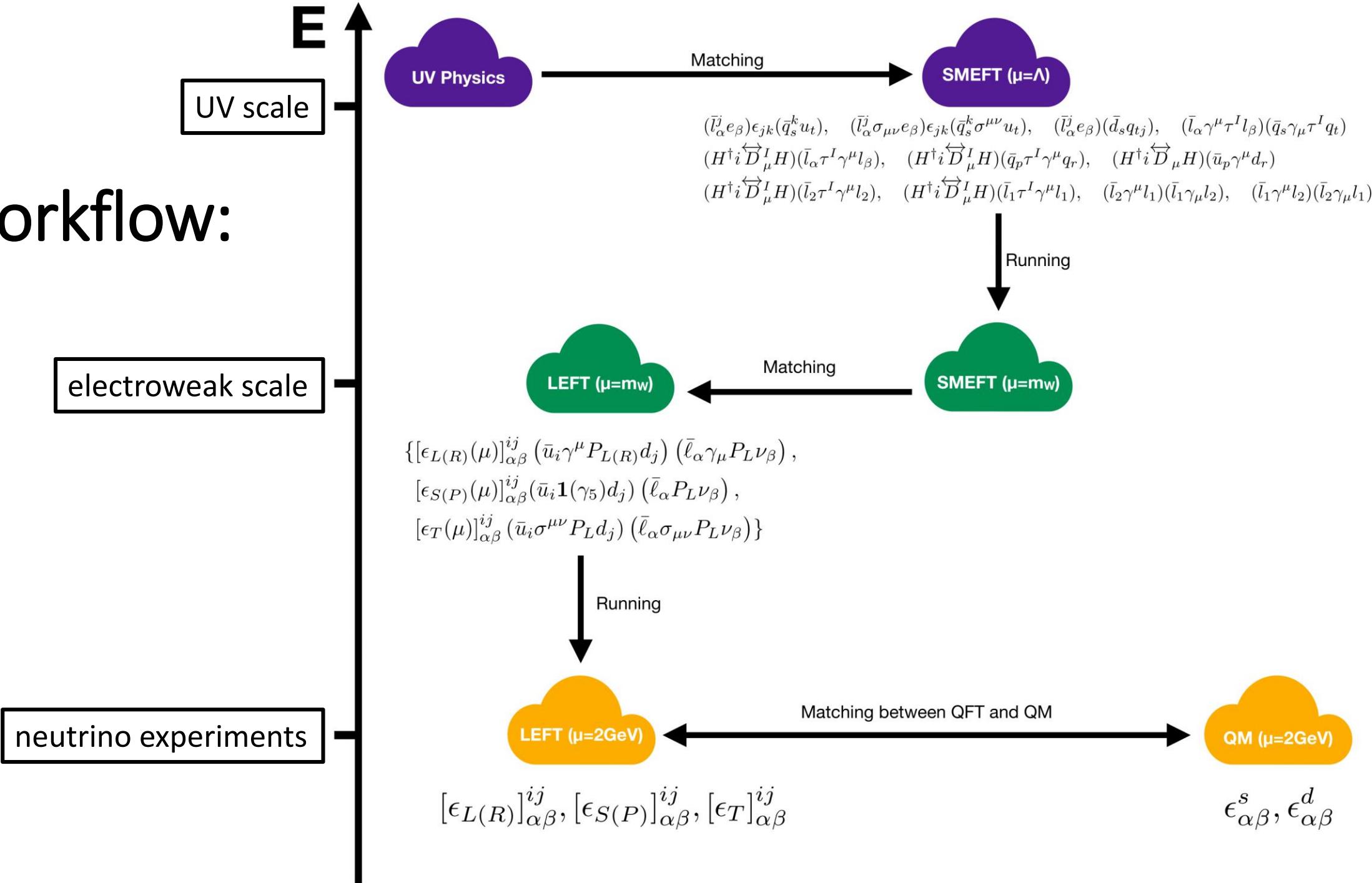
Wilson coefficients

Effective operators starting from dim-5

Scale of the new physics

SMEFT expresses new physics with SM fields and operators.

The workflow:



Interpreting neutrino NSI in SMEFT

Neutrino NSI formalism

Matter NSI:

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

Source NSI:

$$|v_\alpha^s\rangle = \frac{(1 + \epsilon^s)_{\alpha\gamma}}{N_\alpha^s} |v_\gamma^s\rangle$$

Detection NSI:

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

$$N_\alpha^s = \sqrt{(1 + \epsilon^s)(1 + \epsilon^{s\dagger})_{\alpha\alpha}} \text{ and } N_\beta^d = \sqrt{(1 + \epsilon^{d\dagger})(1 + \epsilon^d)_{\beta\beta}}$$

Review: [arXiv:1209.2710](https://arxiv.org/abs/1209.2710)

Interpreting neutrino NSI in SMEFT

LEFT formalism

$$\begin{aligned}\mathcal{L}_{CC} \supset -2\sqrt{2} G_F V_{ud}^{\text{SM}} & \left\{ [1 + \epsilon_L]_{\alpha\beta}^{ij} (\bar{u}_i \gamma^\mu P_L d_j) (\bar{l}_\alpha \gamma_\mu P_L v_\beta) + [\epsilon_R]_{\alpha\beta}^{ij} (\bar{u}_i \gamma^\mu P_R d_j) (\bar{l}_\alpha \gamma_\mu P_L v_\beta) \right. \\ & + \frac{1}{2} [\epsilon_S]_{\alpha\beta}^{ij} (\bar{u}_i d_j) (\bar{l}_\alpha P_L v_\beta) - \frac{1}{2} [\epsilon_P]_{\alpha\beta}^{ij} (\bar{u}_i \gamma_5 d_j) (\bar{l}_\alpha P_L v_\beta) \\ & \left. + \frac{1}{4} [\epsilon_T]_{\alpha\beta}^{ij} (\bar{u}_i \sigma^{\mu\nu} P_L d_j) (\bar{l}_\alpha \sigma_{\mu\nu} P_L v_\beta) + \text{h. c.} \right\}\end{aligned}$$

$i, j = 1, 2, 3$ for quarks and $\alpha, \beta = e, \mu, \tau$ for leptons

Interpreting neutrino NSI in SMEFT

Matching formulas for neutrino sources

Groundwork laid in
arXiv:1910.02971

Beta decay $\epsilon_{e\beta}^s = \left[\epsilon_L - \epsilon_R - \frac{g_T}{g_A} \frac{m_e}{f_T(E_\nu)} \epsilon_T \right]_{e\beta}^*$

Tensor charge
Axial-vector charge
Tensor form factor

Pion decay $\epsilon_{\mu\beta}^s = \left[\epsilon_L - \epsilon_R - \frac{m_\pi^2}{m_\mu(m_u - m_d)} \epsilon_P \right]_{\mu\beta}^*$

nuclear reactors

superbeams

Interpreting neutrino NSI in SMEFT

Matching formula for neutrino detection (reactor only)

Inverse beta decay $\epsilon_{\beta e}^d = \left[\epsilon_L + \frac{1 - 3g_A^2}{1 + 3g_A^2} \epsilon_R - \frac{m_e}{E_\nu - \Delta} \left(\frac{g_S}{1 + 3g_A^2} \epsilon_S - \frac{3g_A g_T}{1 + 3g_A^2} \epsilon_T \right) \right]_{e\beta}$

Scalar, axial and tensor charges

Antineutrino energy:
 $E_\nu \sim 2 \text{ MeV}$

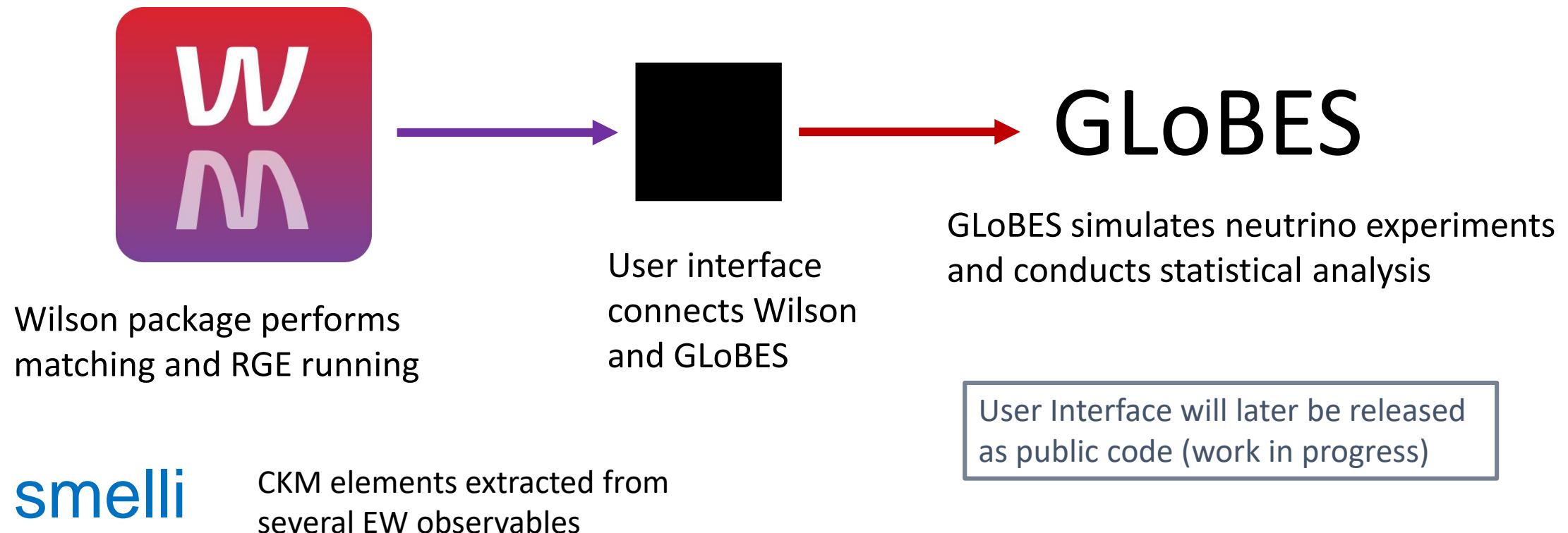
Difference between proton and neutron masses:
 $\Delta = m_n - m_p \approx 1.3 \text{ MeV}$

CAVEAT!

All interactions \sim Gamow-Teller

Interpreting neutrino NSI in SMEFT

The workflow of the numerical analysis:



Applications in neutrino experiments

Concrete examples:

Top-down approach

- UV model is known
- Effects directly calculable
- Example: scalar leptoquark

Bottom-up approach

- UV model is not known
- Experiments constrain cut-off scale and Wilson coefficients

SOME CAVEATS: Theoretical uncertainties, not all UV models presentable in SMEFT, probing NP similar to sailing in an open sea...

Applications in neutrino experiments

Example of top-down approach: **Scalar leptoquark**

Model setup:

Scalar leptoquark S with quantum numbers $(\bar{3}, 1, 1/3)$

$$\begin{aligned}\mathcal{L}_{\text{LQ}} = & \left| D_\mu S \right|^2 - M_1^2 |S|^2 - \lambda_{H1} |H|^2 |S|^2 - \frac{c}{2} |S|^4 \\ & + ((\lambda^L)_{i\alpha} \bar{q}_i^c \epsilon l_\alpha + (\lambda^R)_{i\alpha} \bar{u}_i^c e_\alpha) S_1 + \text{h. c.}\end{aligned}$$

Applications in neutrino experiments

Scalar leptoquark

$$\mathcal{O}_{lq}^{(1)} = (\bar{l}\gamma^\mu l)(\bar{q}\gamma_\mu q) \quad \mathcal{O}_{lq}^{(3)} = (\bar{l}\gamma^\mu \sigma^I l)(\bar{q}\gamma_\mu \sigma^I q) \quad \mathcal{O}_{lequ}^{(1)} = (\bar{l}^r e)\epsilon_{rs}(\bar{q}^s u)$$

$$\mathcal{O}_{lequ}^{(3)} = (\bar{l}^r \sigma^{\mu\nu} e)\epsilon_{rs}(\bar{q}^s \sigma_{\mu\nu} u) \quad \mathcal{O}_{eu} = (\bar{e}\gamma^\mu e)(\bar{u}\gamma_\mu u)$$

$$C_{lq_{\alpha\beta ij}}^{(1)} = \frac{\lambda_{i\alpha}^{L*} \lambda_{j\beta}^L}{4M^2}$$

$$C_{lq_{\alpha\beta ij}}^{(3)} = -\frac{\lambda_{i\alpha}^{L*} \lambda_{j\beta}^L}{4M^2}$$

$$C_{lequ_{\alpha\beta ij}}^{(1)} = \frac{\lambda_{j\beta}^R \lambda_{i\alpha}^{L*}}{2M^2}$$

$$C_{lequ_{\alpha\beta ij}}^{(3)} = -\frac{\lambda_{j\beta}^R \lambda_{i\alpha}^{L*}}{8M^2}$$

$$C_{eu_{\alpha\beta ij}} = \frac{\lambda_{i\alpha}^{R*} \lambda_{j\beta}^L}{2M^2}$$

Applications in neutrino experiments

Non-standard interactions in SMEFT confronted with
terrestrial neutrino experiments [arXiv:2011.14292](https://arxiv.org/abs/2011.14292)

Long-baseline experiments:

- Tokai-to-Kamioka (T2K) experiment
- Numi Off-axis ν_e Appearance (NOvA) experiment

Target of the analysis:

Source NSI in pion decay

Reactor experiments:

- Daya Bay neutrino experiment
- Double Chooz experiment
- Reactor Experiment for Neutrino Oscillation (RENO)

Target of the analysis:

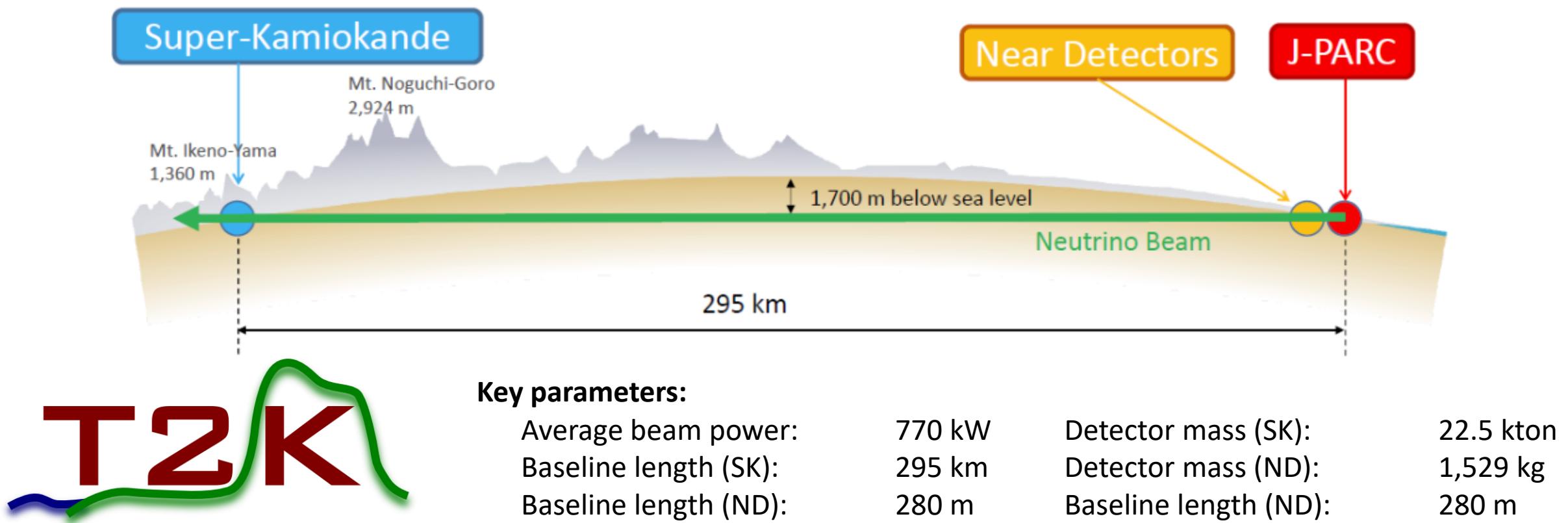
Source NSI in beta decay

*Detection NSI in inverse
beta decay*

Applications in neutrino experiments

Schematics of the T2K experiment:

Production method: pion decay
Detection method: cherenkov radiation



Applications in neutrino experiments

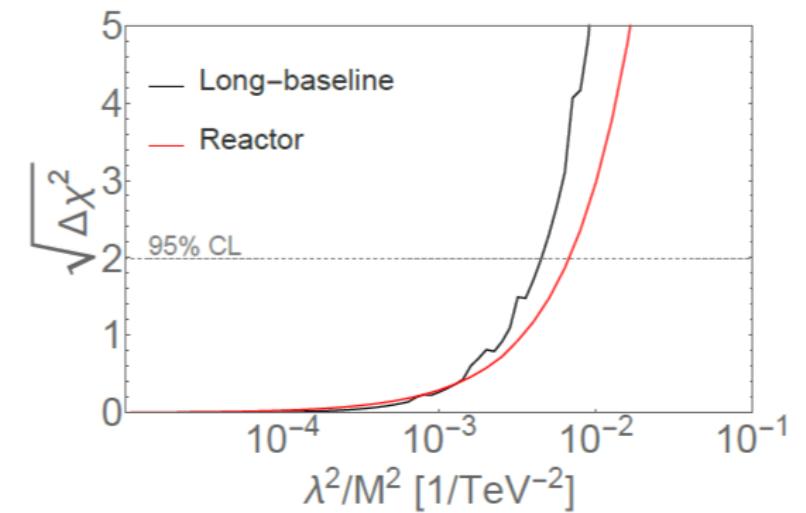
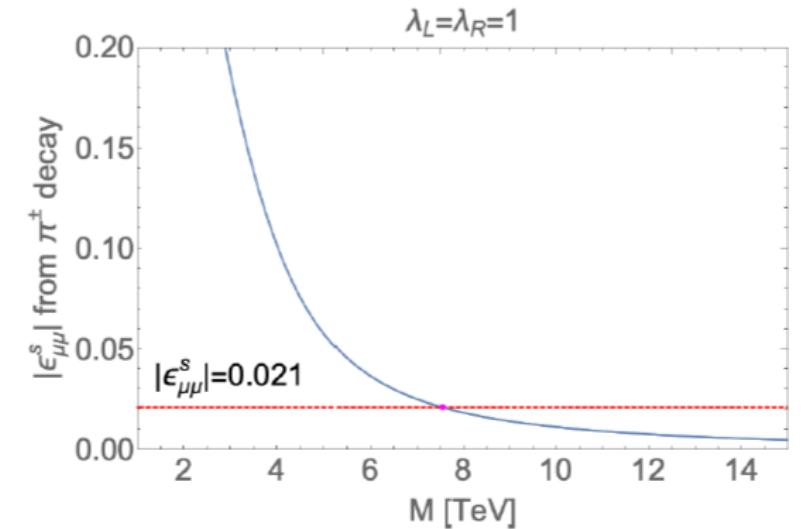
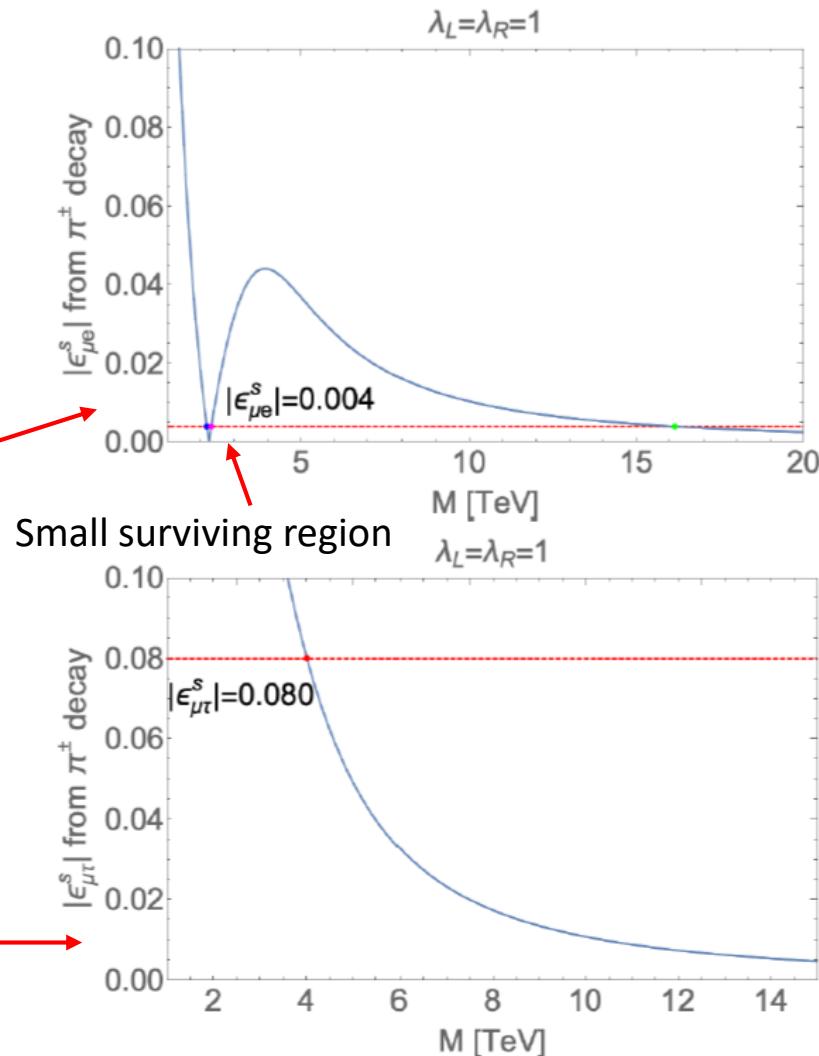
arXiv:2011.14292

Scalar leptoquark

Numerical results

Best constraint:

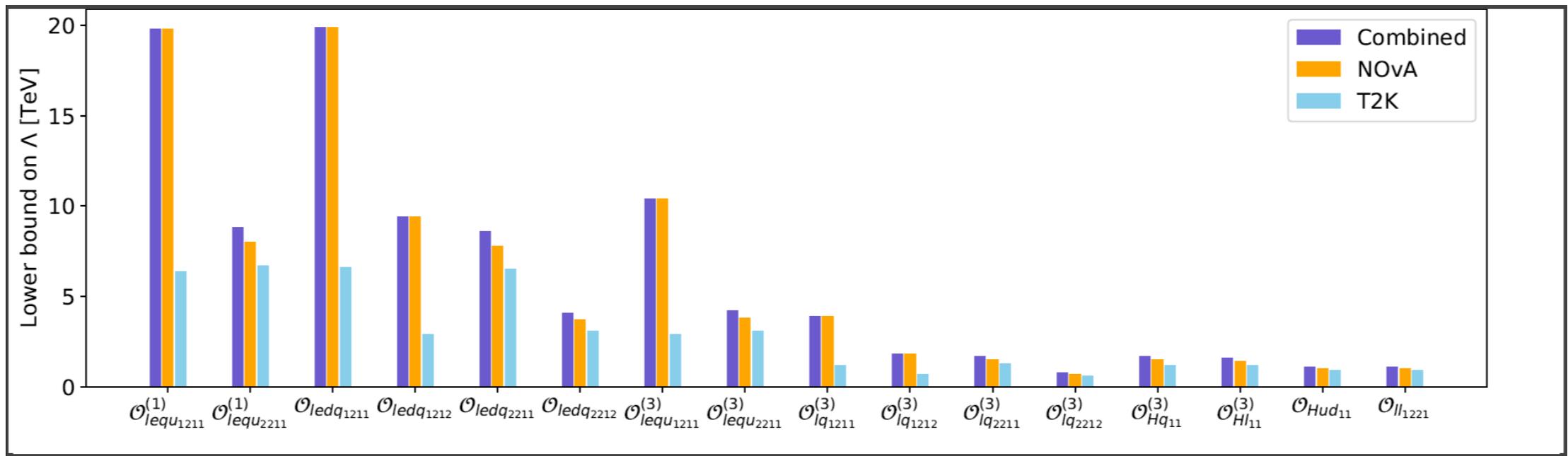
$M > 16 \text{ TeV}$



Applications in neutrino experiments

Example of bottom-down approach:

[arXiv:2011.14292](https://arxiv.org/abs/2011.14292)

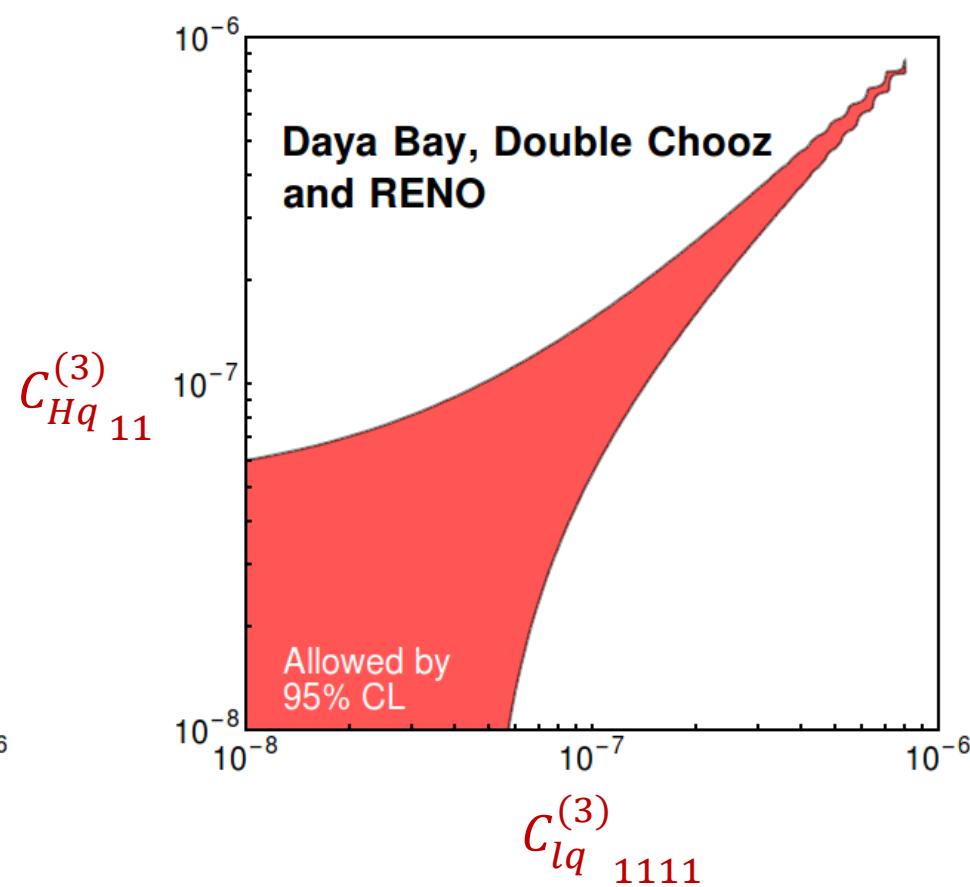
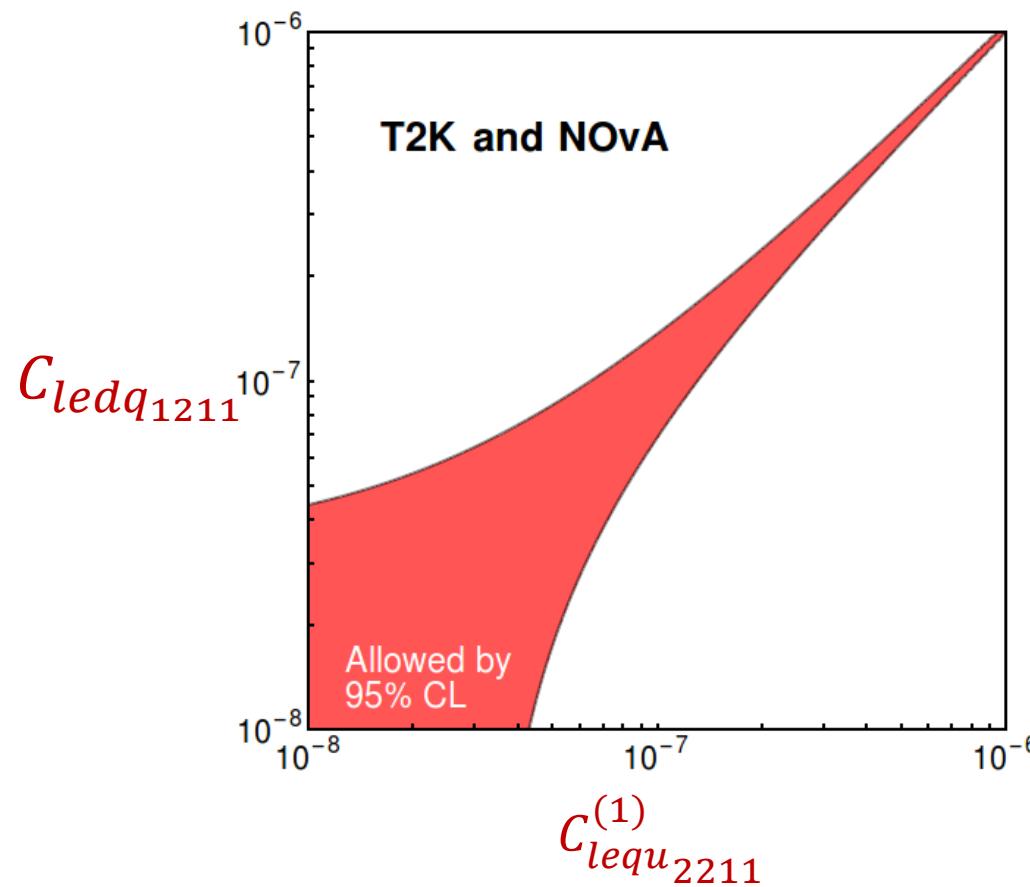


T2K and NOvA constraints on individual operators at 95% CL

Applications in neutrino experiments

Correlation between multiple operators:

[arXiv:2011.14292](https://arxiv.org/abs/2011.14292)

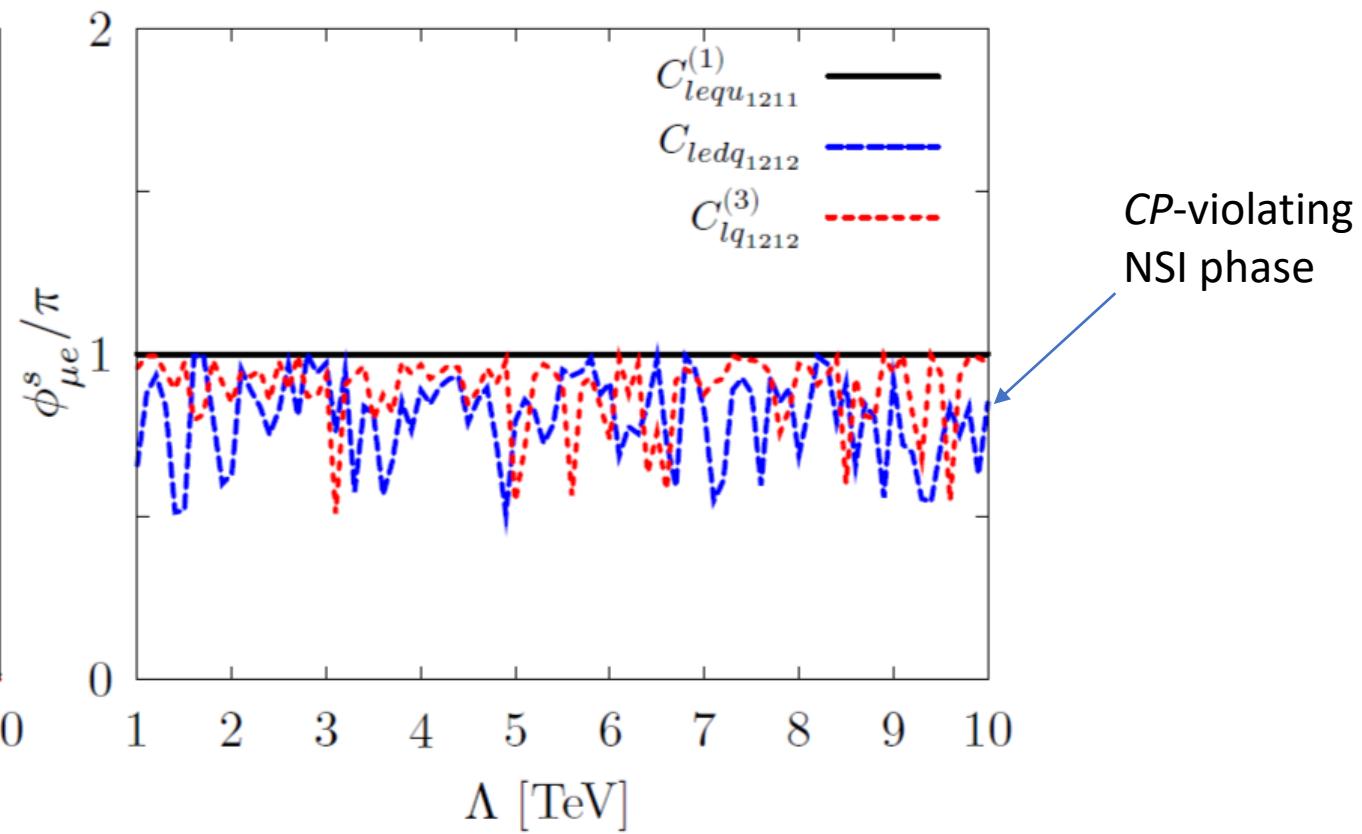
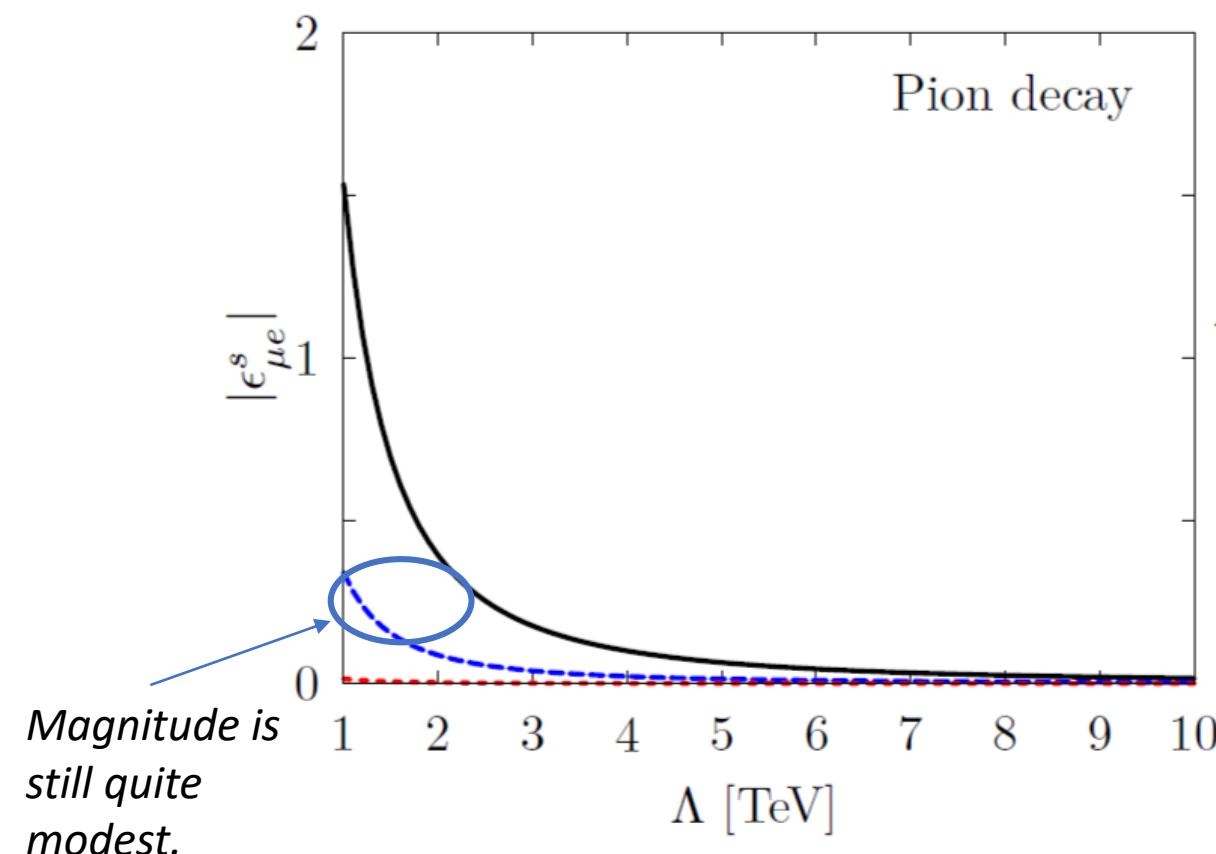


Cut-off scale:
 $\Lambda = 1 \text{ TeV}$

Applications in neutrino experiments

Leptonic CP violation from RGE running:

[arXiv:2011.14292](https://arxiv.org/abs/2011.14292)



Next-generation experiments

Exploring SMEFT-induced non-standard interactions from COHERENT to neutrino oscillations [arXiv:2106.15800](https://arxiv.org/abs/2106.15800)

Long-baseline neutrino experiments:

- Tokai-to-HyperKamiokande (T2HK)
- Deep Underground Neutrino Experiment (DUNE)

Targets of the analysis:

Source NSI in pion decay

Reactor neutrino experiment:

- Jiangmen Underground Neutrino Observatory (JUNO)
- Taishan Antineutrino Observatory (TAO)

Source NSI in beta decay

Coherent elastic ν -nucleus scattering experiment:

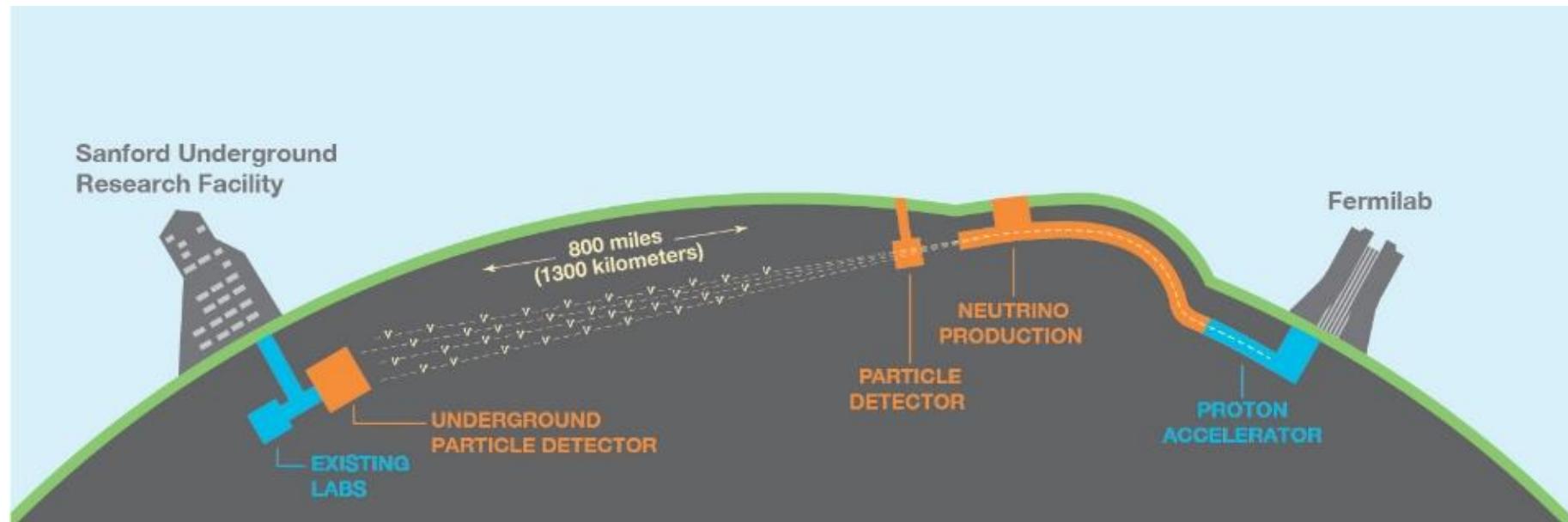
- COHERENT experiment

Detection NSI in inverse beta decay

Matter NSI in propagation

Next-generation experiments

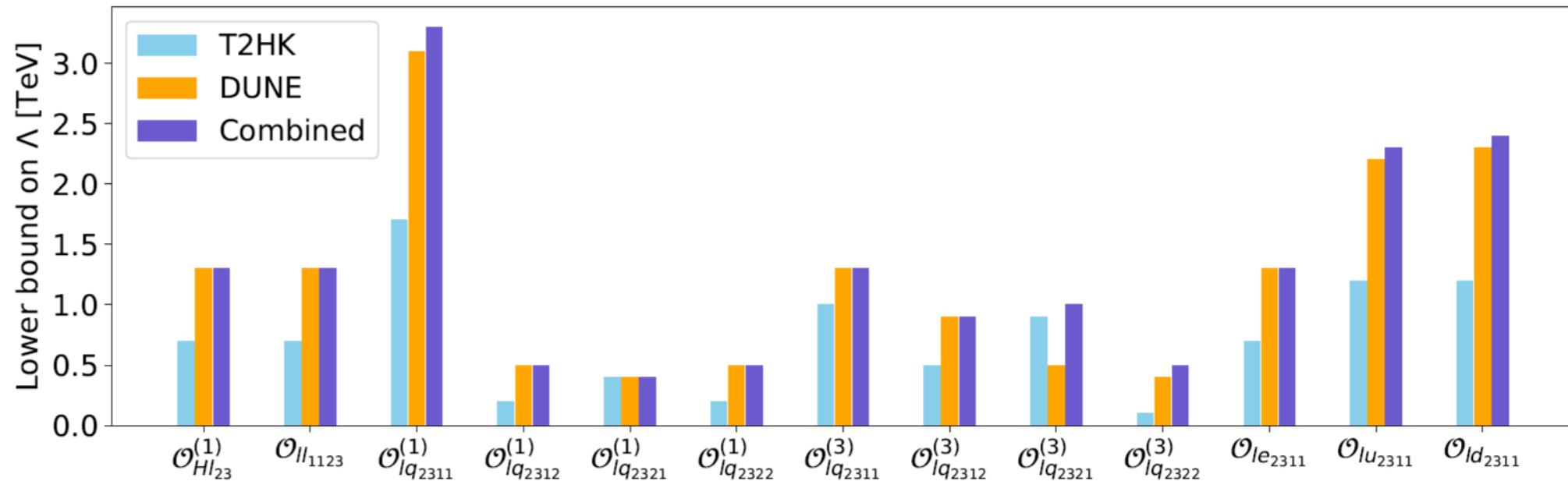
T2HK and DUNE are the next-generation LBL experiments designed to measure δ_{CP} . Data taking will begin in 2026 or 2027.



Schematical view of Deep Underground Neutrino Experiment

Next-generation experiments

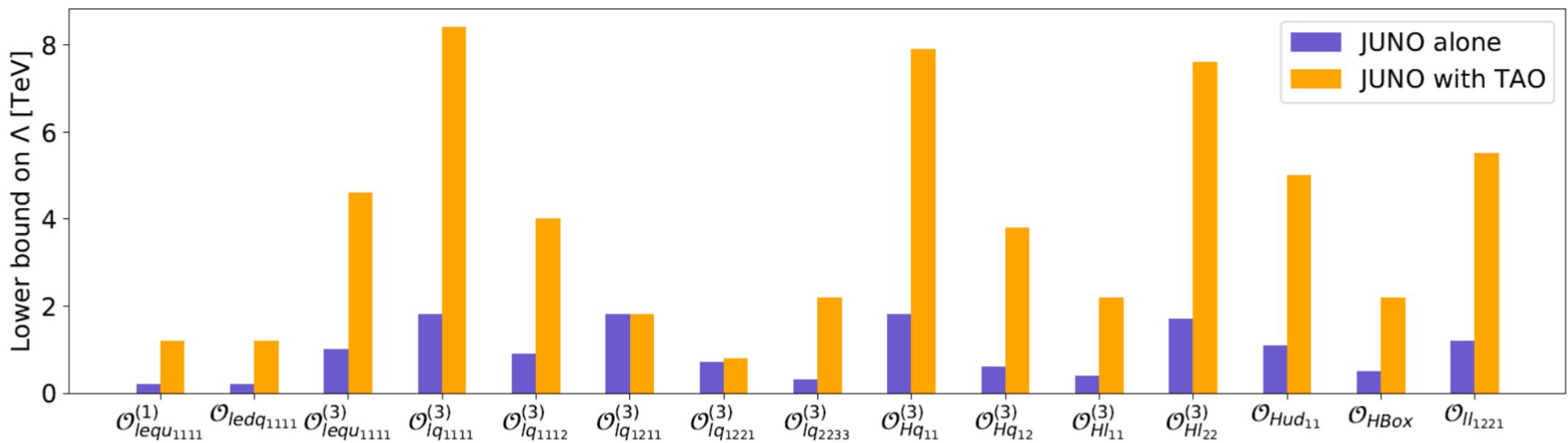
T2HK and DUNE constraints on SMEFT operators:



More than 100 operators accessible!

Next-generation experiments

JUNO and TAO constraints on SMEFT operators:



Complementarity with long-baseline experiments

Next-generation experiments

New Physics in COHERENT:

$$\frac{d\sigma_{\nu N}}{dE_R} = \frac{G_F^2 M_N}{\pi} \left(1 - \frac{M_N E_R}{2E_\nu^2} \right) (Z g_p^V F_p(q^2) + N g_n^V F_n(q^2))^2$$

target nucleus mass
recoil energy
nuclear form factors

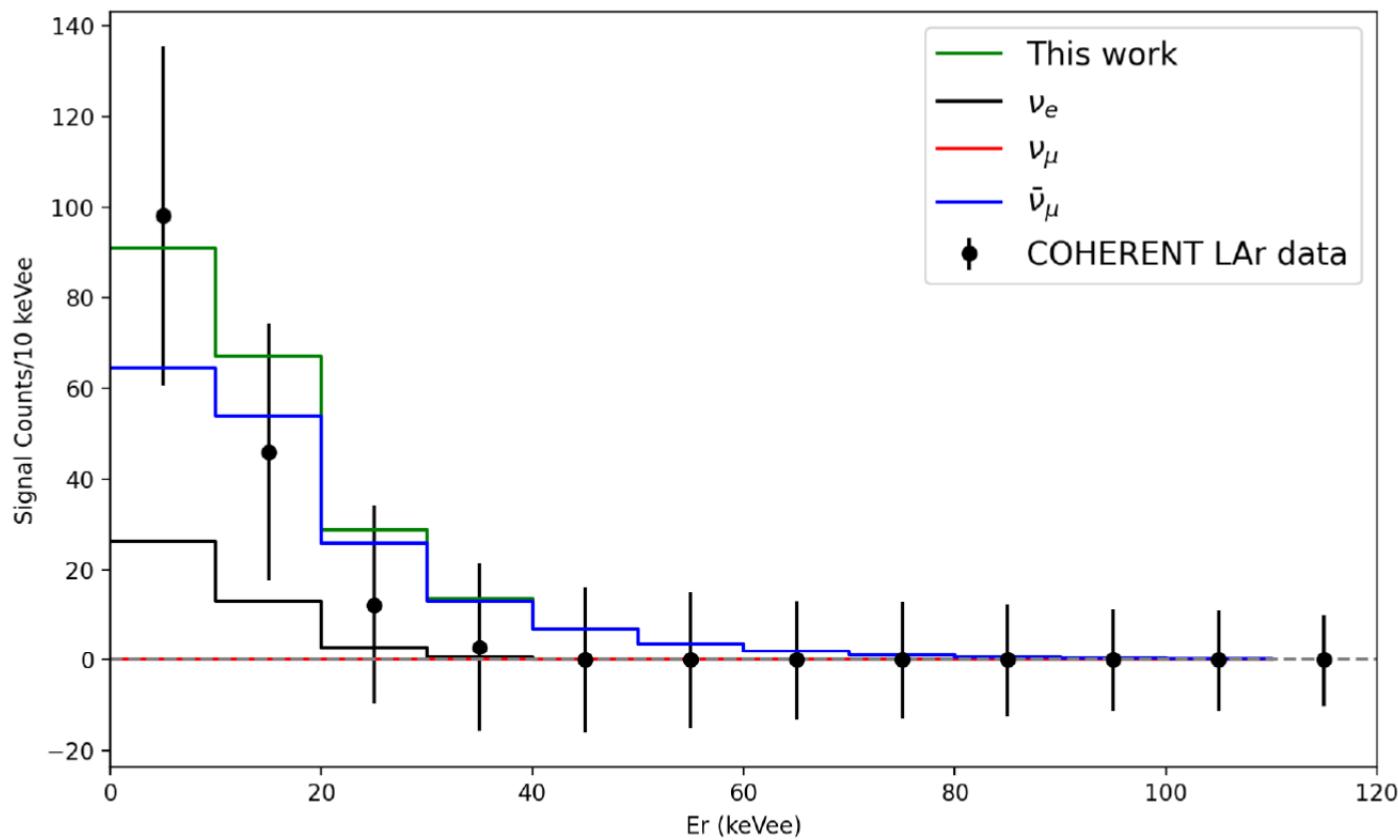
neutrino energy

$$g_p^V = \frac{1}{2} - 2 \sin^2 \theta_W$$
$$g_n^V = -\frac{1}{2}$$

COHERENT with CsI target 1804.09459, Ar target 2006.12659

Next-generation experiments

COHERENT data with LAr detector arXiv:2006.12659

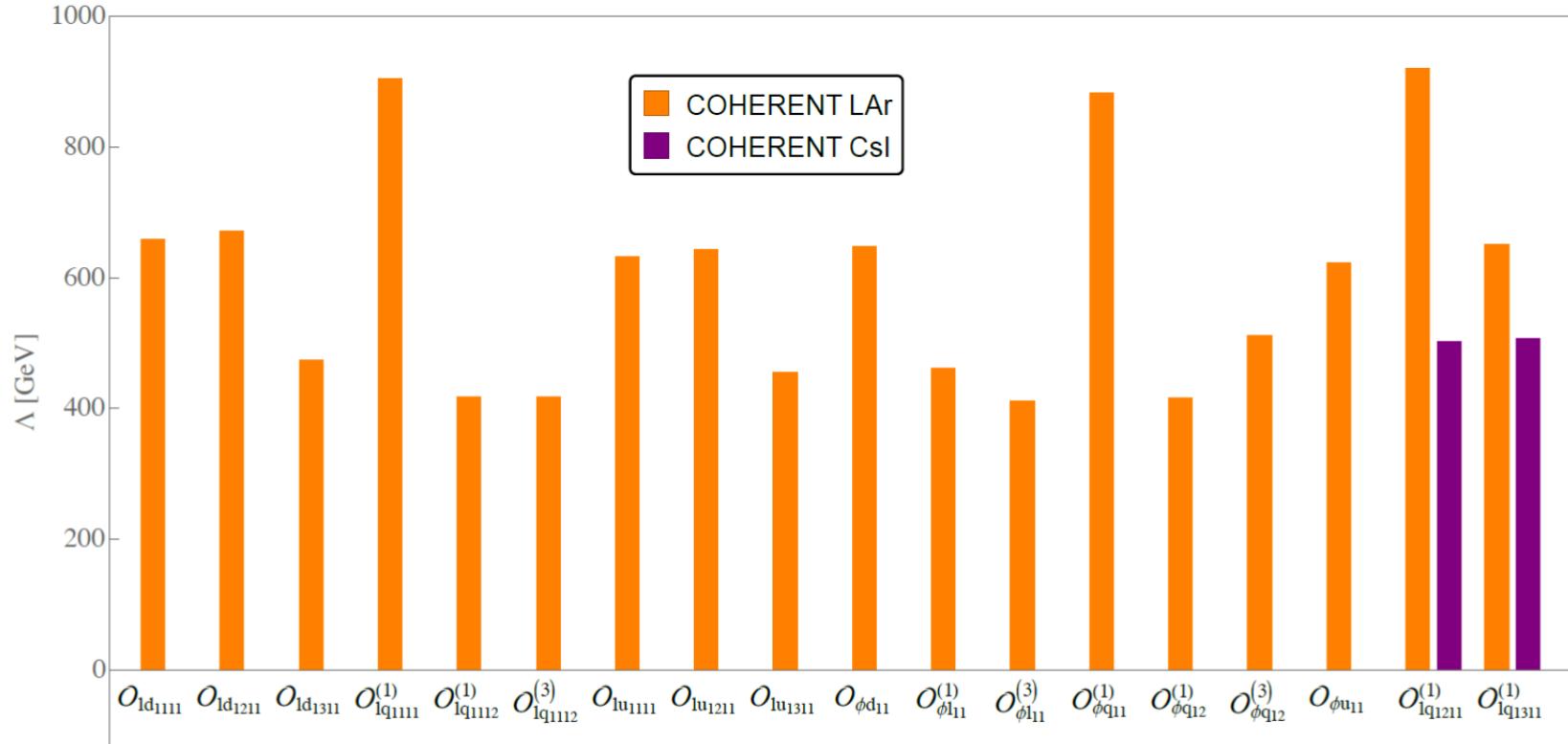


arXiv:2106.15800

Next-generation experiments

arXiv:2106.15800

COHERENT constraints on SMEFT operators:



Still limited by data...

Summary and outlook

- Standard Model confronted by anomalies and tensions $\sim 3\text{-}4 \sigma$ CL
- In absence of new discoveries, EFT approach becomes attractive
- Neutrino experiments offer a powerful probe for New Physics
 - Matching process from UV models to neutrino experiments
 - Top-down: Leptoquark toy model example
 - Bottom-up: Neutrino constraints on SMEFT operators
- Next-generation experiments show a promising landscape
 - Immense number of dim-6 SMEFT operators can be studied with superbeams, reactor experiments, coherent elastic scattering
 - comparability, complementarity
- Future prospects: detection NSI in superbeams, theoretical uncertainties....