Implications on new physics from neutrino non-standard interactions in the EFT framework

Yong Du

email: yongdu@itp.ac.cn

PHENO2021, 26 May, 2021

YD, J-H. Yu, JHEP 05 (2021) 058

YD, H-L. Li, J. Tang, S. Vihonen, J-H. Yu, JHEP 03(2021) 019

YD, H-L. Li, J. Tang, S. Vihonen, J-H. Yu, arXiv:2106.XXXXX

Overview

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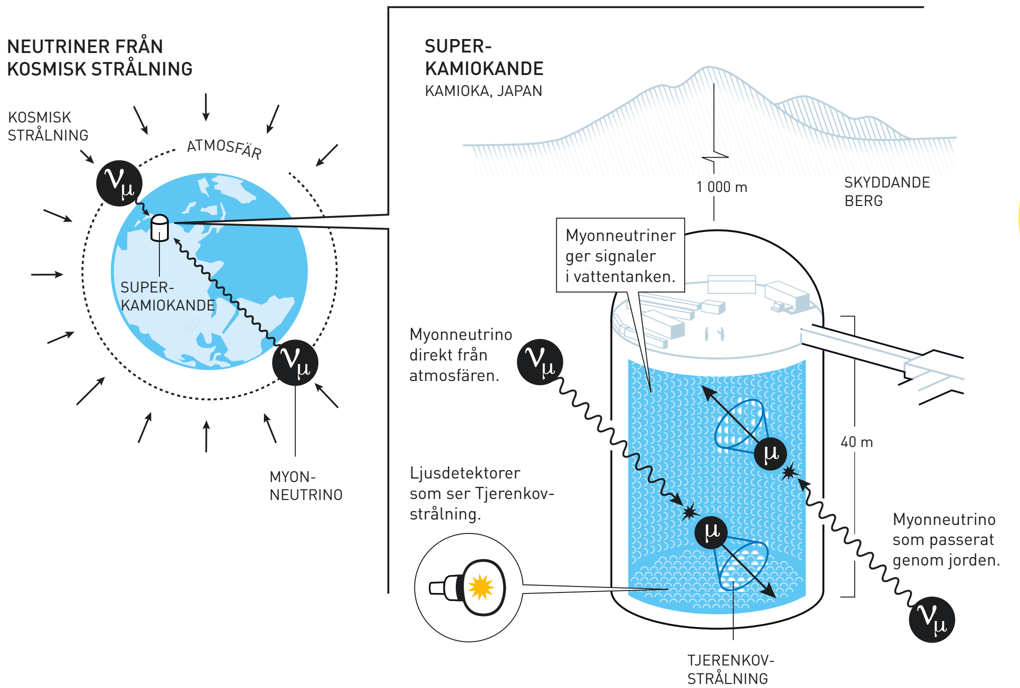

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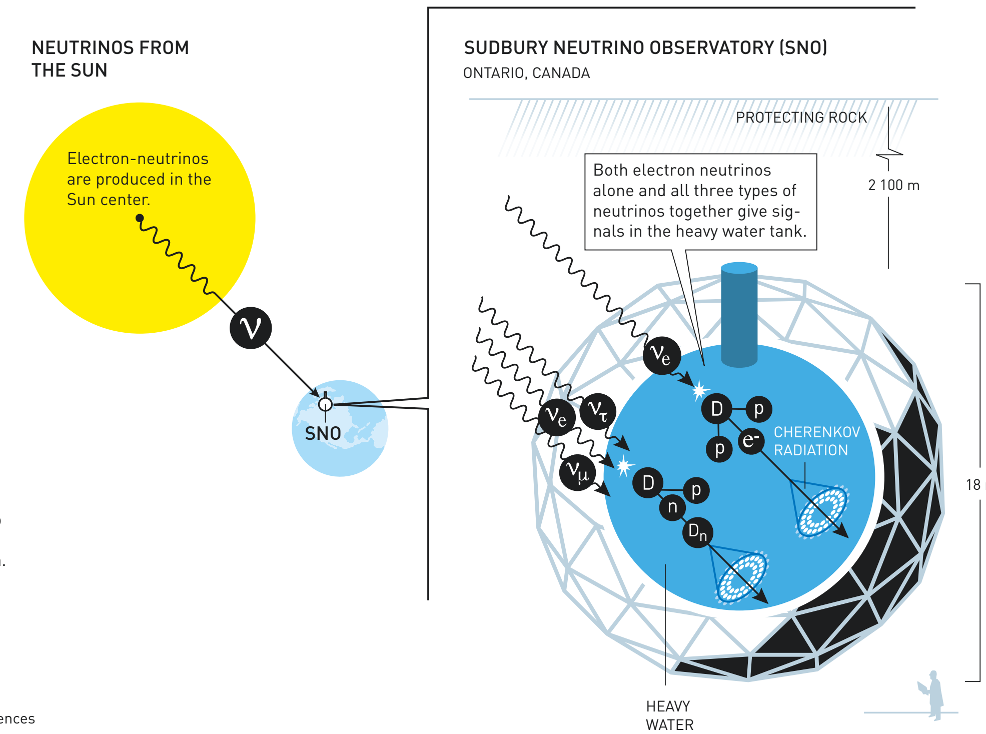

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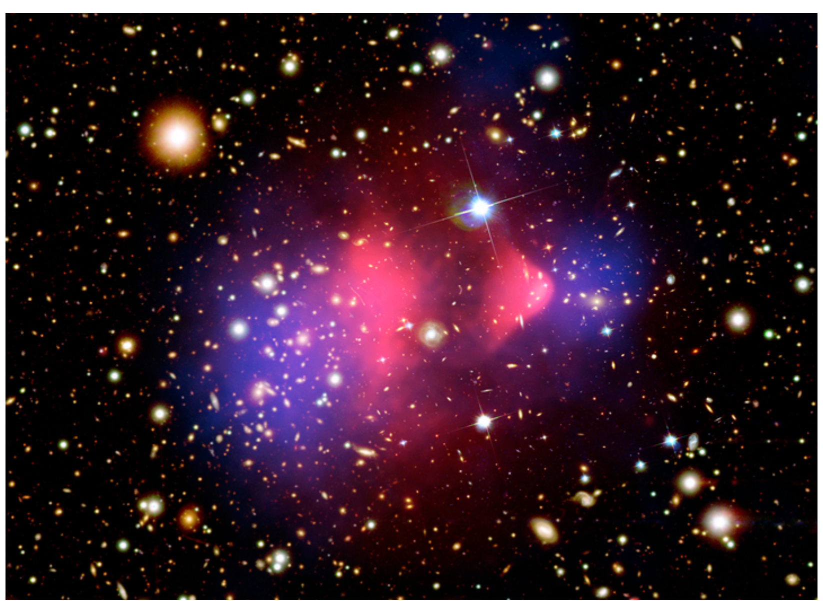
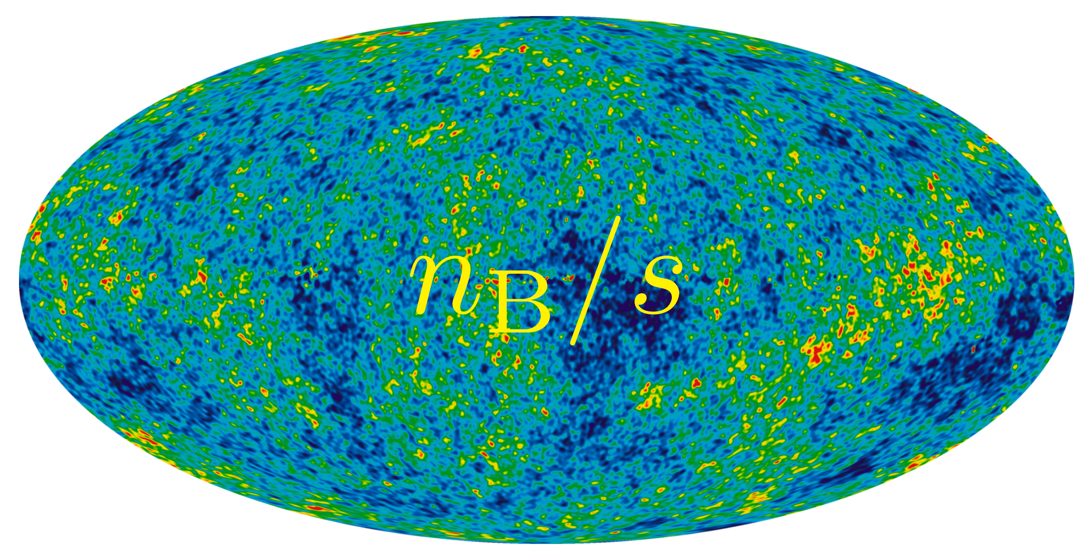
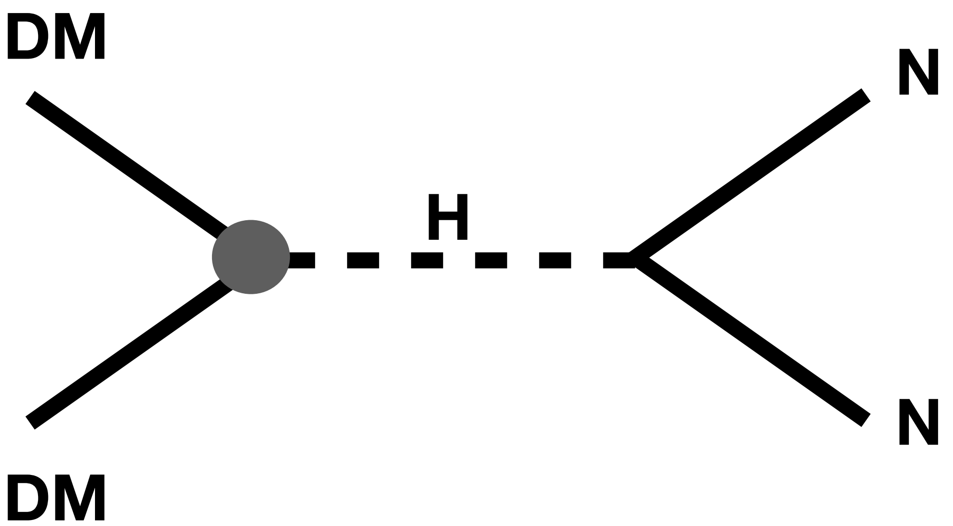




Overview

Σ := Real triplet (1, 3, 0)

$$m_\Sigma < 248\,\mathrm{GeV}\;(\mathrm{LHC})$$



Chiang, Cottin, **YD**, Fuyuto, Ramsey-Musolf, *JHEP* 01 (2021) 198

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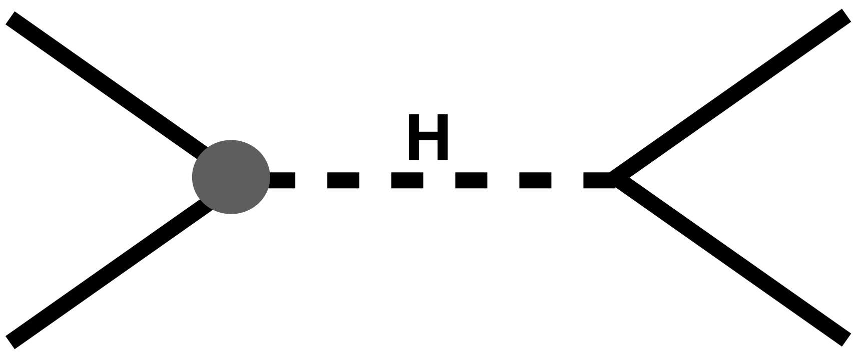
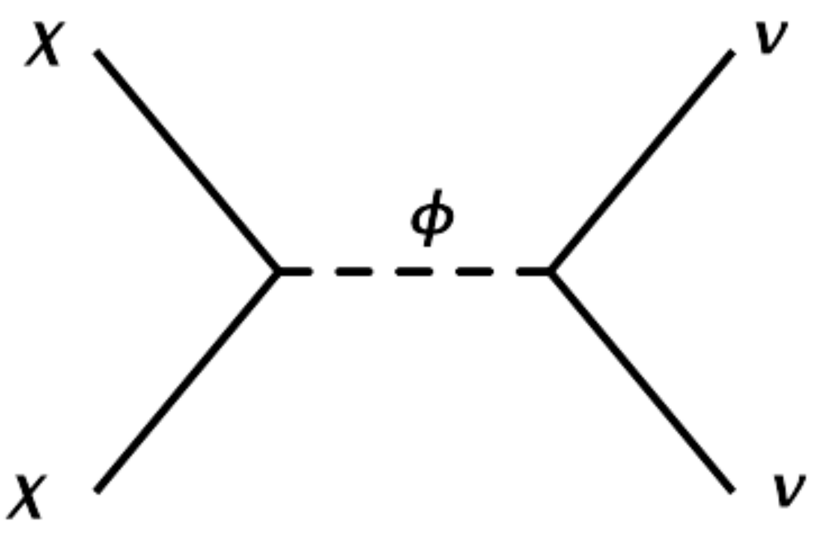
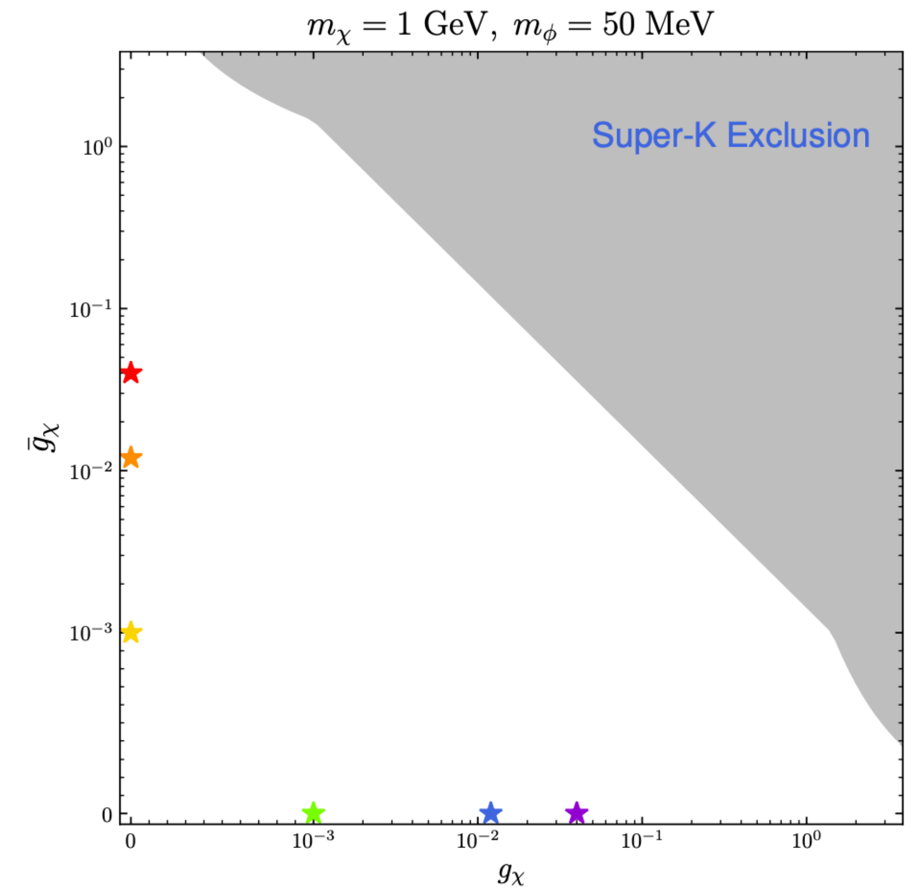


Chiang, Cottin, **YD**, Fuyuto, Ramsey-Musolf, *JHEP* 01 (2021) 198

$$\mathcal{L}_{\mathrm{int}} = -\phi\bar{\chi}(g_\chi + i\bar{g}_\chi\gamma^5)\chi - \phi\bar{\nu}_i(g_\nu^{ij} + i\bar{g}_\nu^{ij}\gamma^5)\nu_j$$





YD, Huang, Li, Yu, *JHEP* 12 (2020) 207

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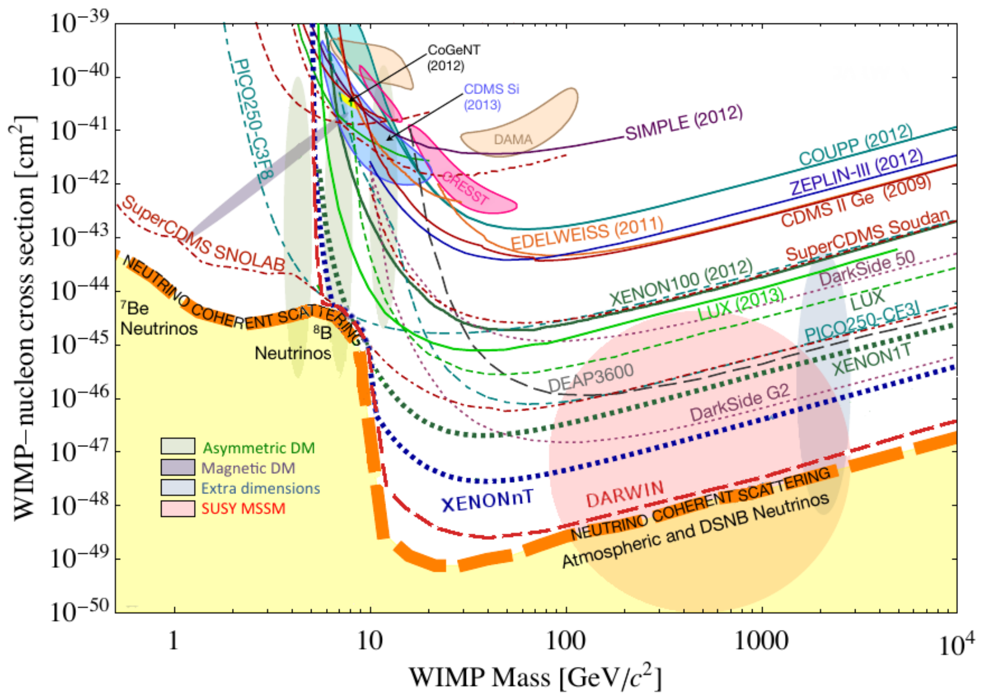

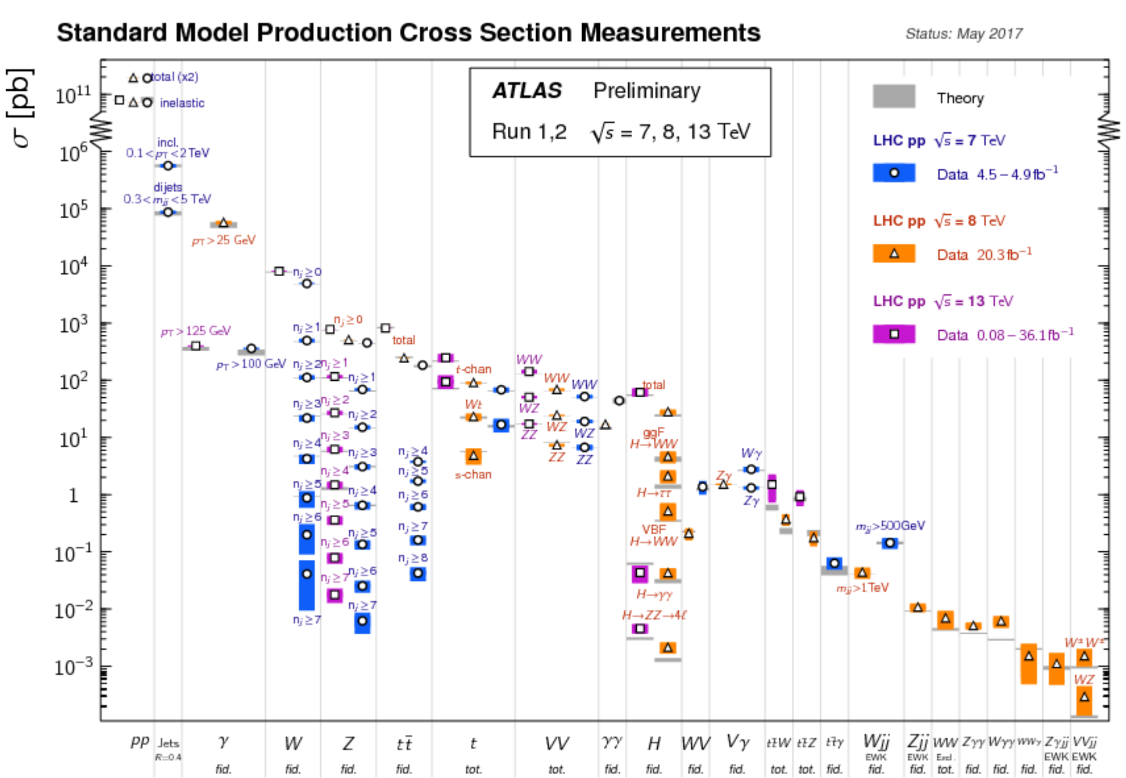

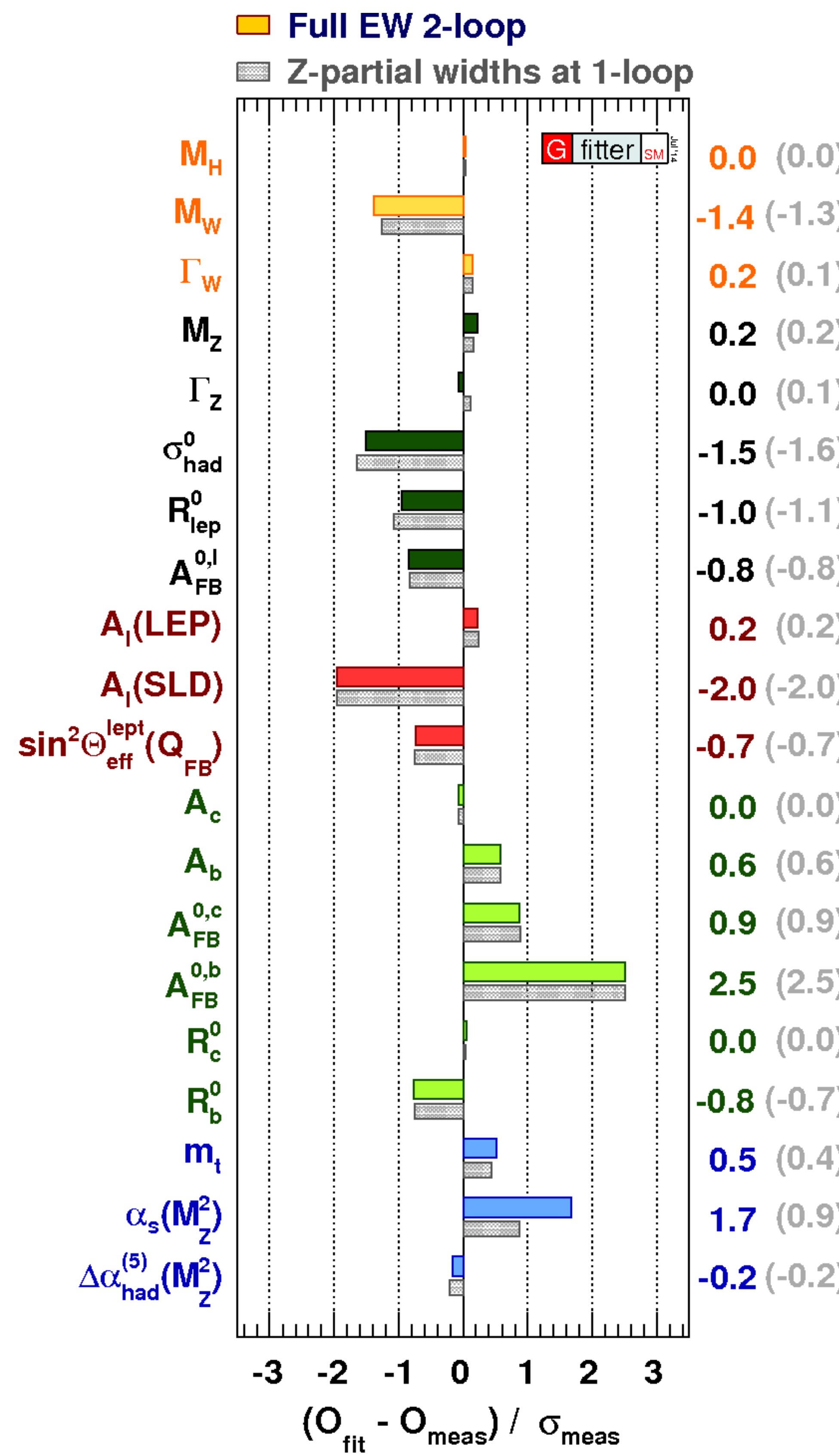

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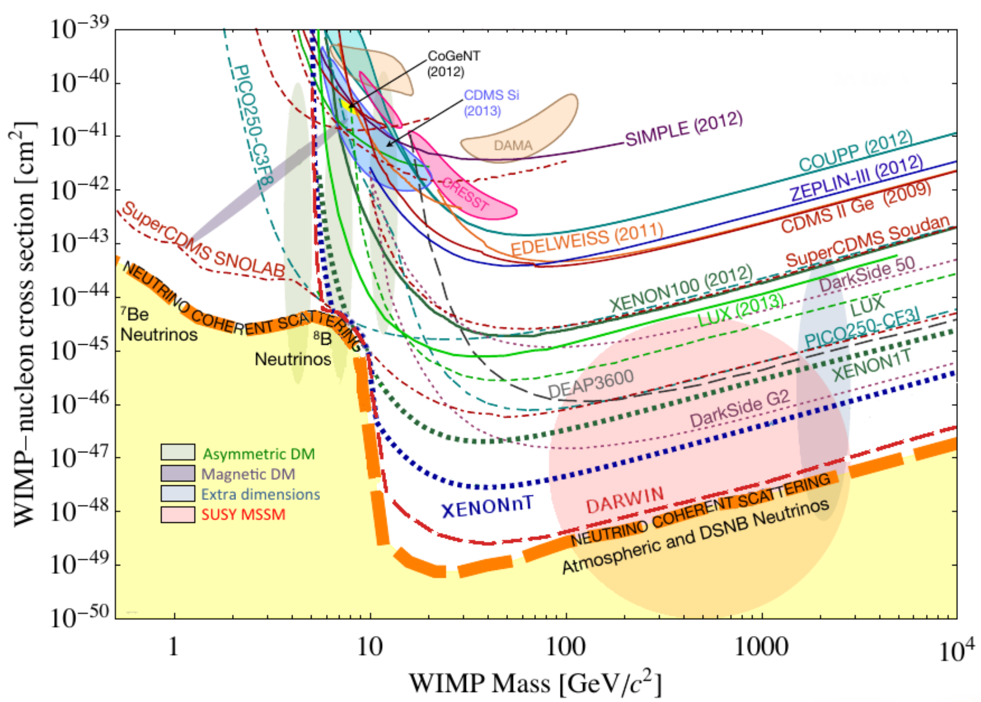

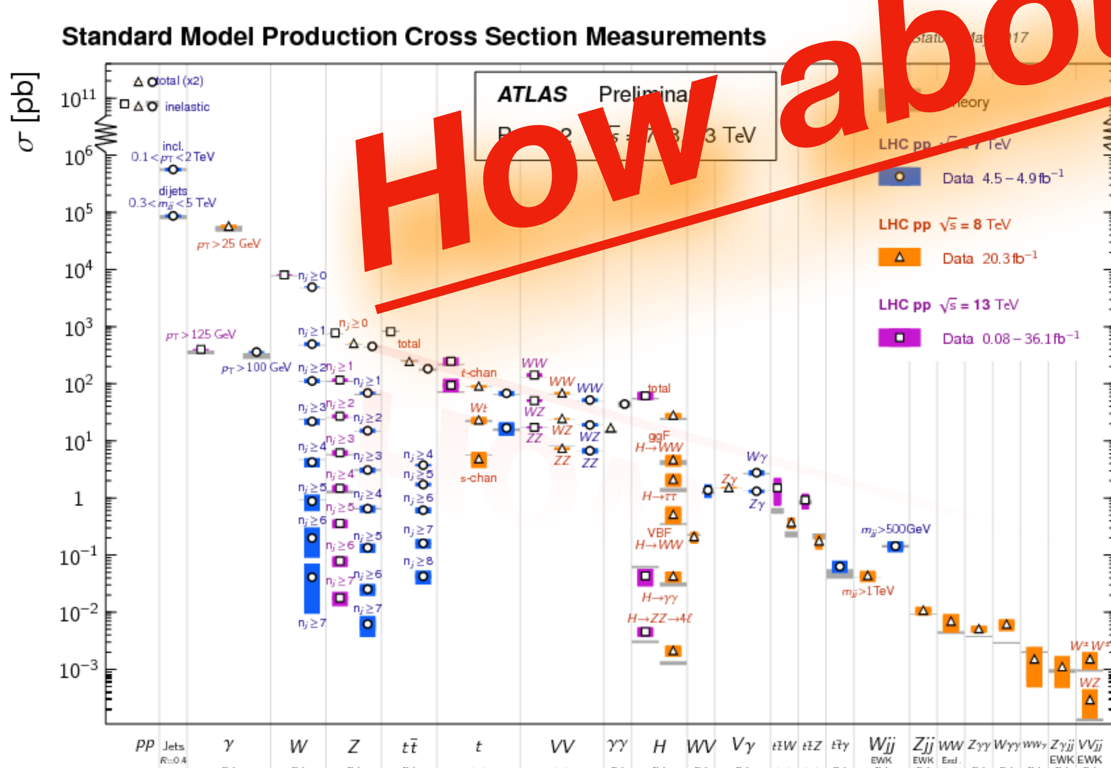

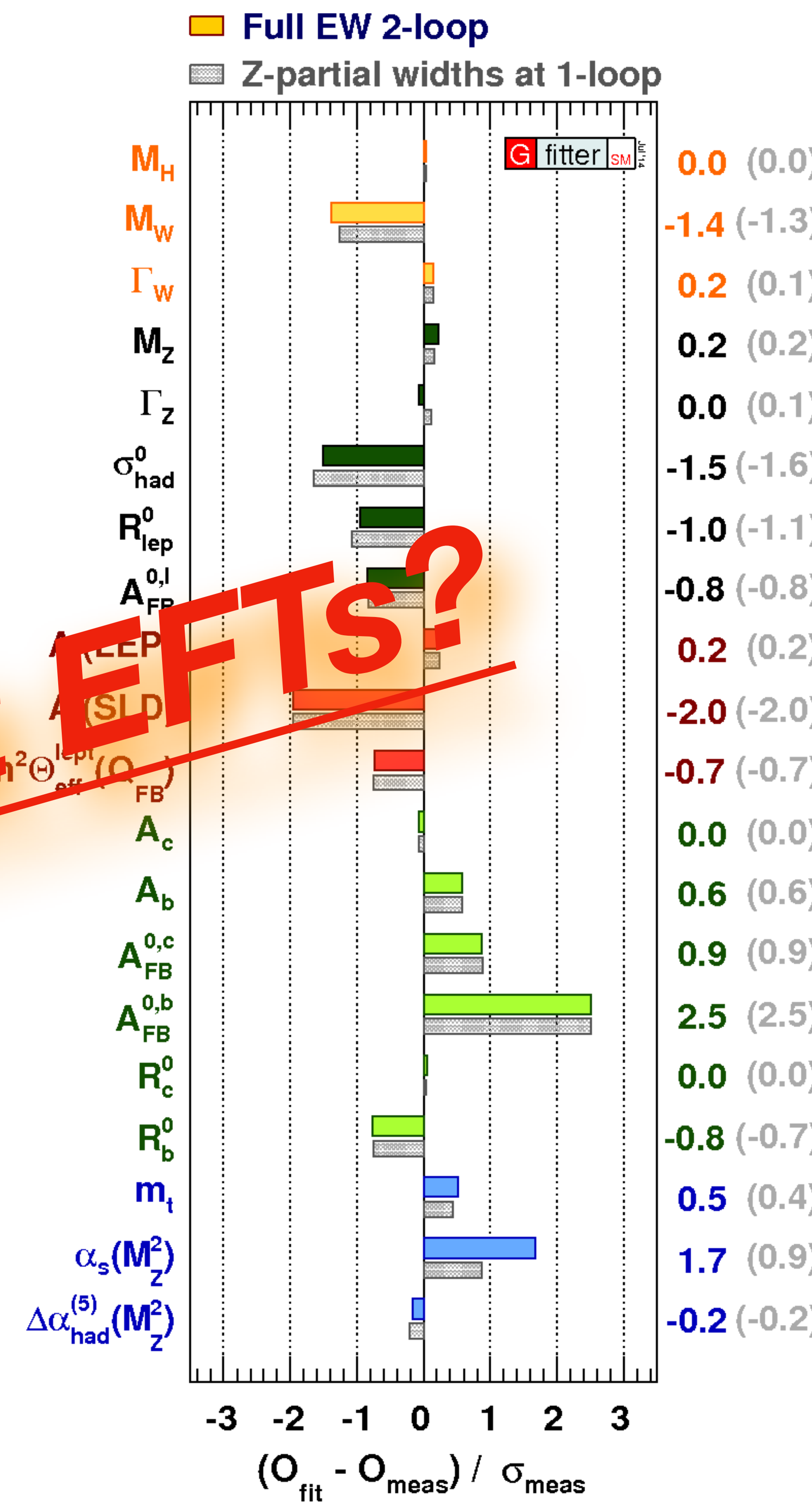

How about EFTs?

Overview

In this talk, I will only focus on neutrino NSIs from an EFT approach

Regina Rameika's talk for an excellent review

Danny Marfatia's talk for general neutrino interactions (GNIs)

CC NSIs

What neutrino experimentalists measure: Mismatch at production and detection

QM:Production/detection parameters

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

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NSI parameter	Upper bound	Experiments
$\left\|\epsilon^s_{\mu e}\right\|$	0.004	
$\left\|\epsilon^s_{\mu\mu}\right\|$	0.021	T2K [21, 72, 73], NOνA [24]
$\left\|\epsilon^s_{\mu\tau}\right\|$	0.080	
$\left\|\epsilon^d_{ee}\right\|$	0.007	
$\left\|\epsilon^d_{\mu e}\right\|$	0.018	
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YD, H-L. Li, J. Tang, S. Vihonen, J-H. Yu, JHEP 03(2021) 019

CC NSIs

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YD, H-L. Li, J. Tang, S. Vihonen, J-H. Yu, JHEP 03(2021) 019

Q: What is the implication on the UV physics?

CC NSIs

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What particle physicists care about: UV physics that induces these interactions

QFT:NSI parameters

$$\mathcal{L} \supset -\frac{2V_{ud}}{v^2}\{ [1+\epsilon_L]_{\alpha\beta} (\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha\gamma_\mu P_L \nu_\beta) + [\epsilon_R]_{\alpha\beta} (\bar{u}\gamma^\mu P_R d)(\bar{\ell}_\alpha\gamma_\mu P_L \nu_\beta)$$

$$+ \frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{u}d)(\bar{\ell}_\alpha P_L \nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{u}\gamma_5 d)(\bar{\ell}_\alpha P_L \nu_\beta) + \frac{1}{4}[\epsilon_T]_{\alpha\beta}(\bar{u}\sigma^{\mu\nu}P_L d)(\bar{\ell}_\alpha \sigma_{\mu\nu} P_L \nu_\beta) + \text{ h.c.}$$

CC NSIs

NSI parameter	Upper bound	Experiments
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$$+\frac{1}{2}[\epsilon_S]_{\alpha\beta}\,(\bar{u}d)\,(\bar{\ell}_\alpha P_L\nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}\,(\bar{u}\gamma_5 d)\,(\bar{\ell}_\alpha P_L\nu_\beta) + \frac{1}{4}[\epsilon_T]_{\alpha\beta}\,(\bar{u}\sigma^{\mu\nu}P_L d)\,(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta) + \text{ h.c.}$$

Connection between the two:

$$\epsilon^s_{e\beta} = \left[\epsilon_L - \epsilon_R - \frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}\epsilon_T\right]^*_{e\beta}, \quad (\beta\text{ decay})$$

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

$$\epsilon^s_{\mu\beta} = \left[\epsilon_L - \epsilon_R - \frac{m_\pi^2}{m_\mu(m_u+m_d)}\epsilon_P\right]^*_{\mu\beta}, \quad (\text{pion decay})$$

Falkowski, Gonzalez-Alonso, Tabrizi, JHEP11(2020)048

CC NSIs

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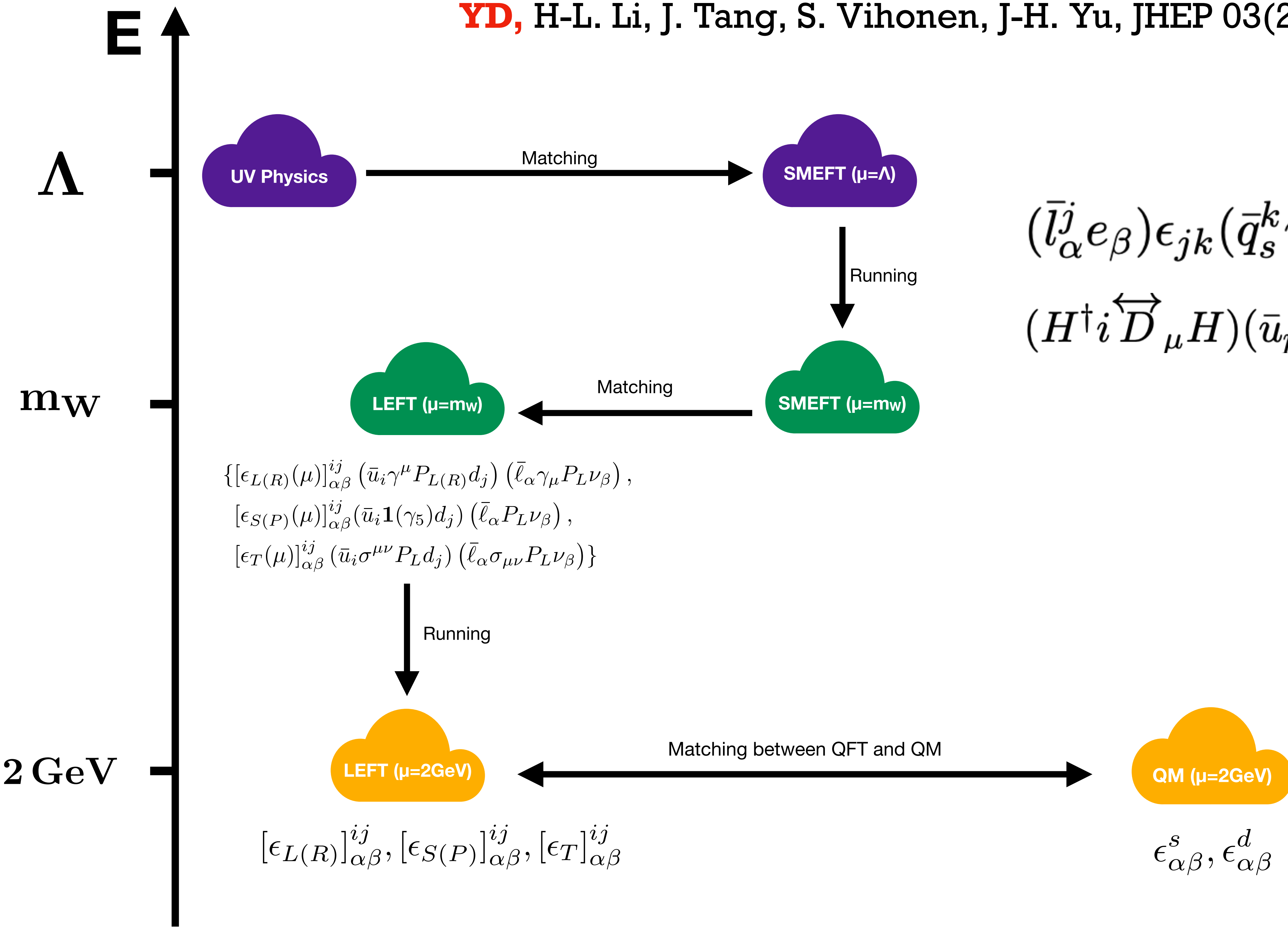


$$(\bar{l}^j_\alpha e_\beta)\epsilon_{jk}(\bar{q}^k_s u_t)$$

$$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu d_r)$$

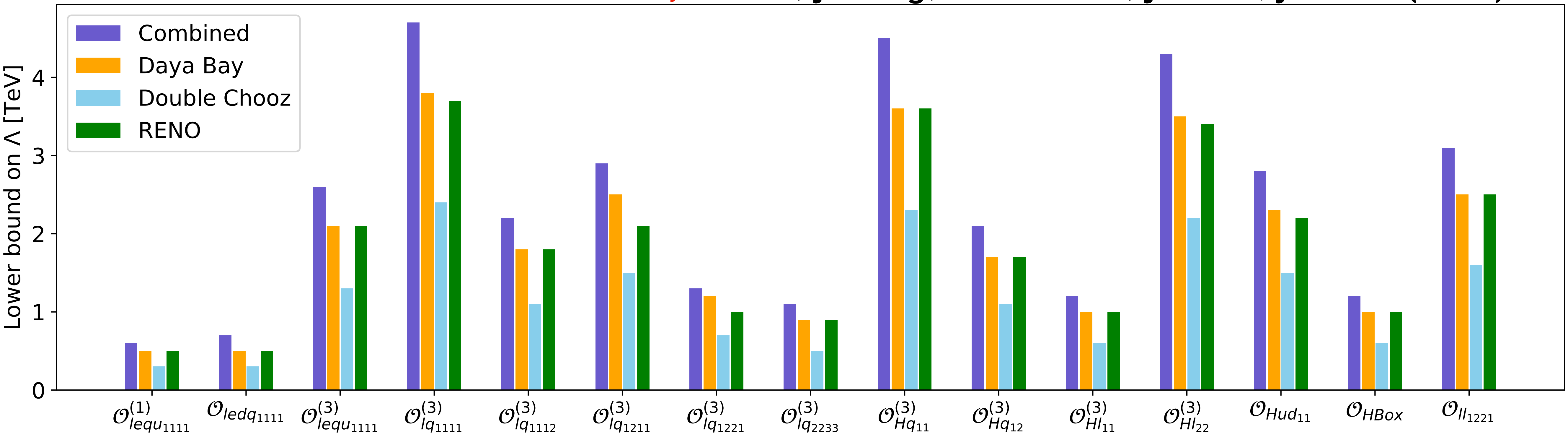
$$\{[\epsilon_{L(R)}(\mu)]^{ij}_{\alpha\beta}\left(\bar{u}_i\gamma^\mu P_{L(R)} d_j\right)\left(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta\right),$$
$$[\epsilon_{S(P)}(\mu)]^{ij}_{\alpha\beta}(\bar{u}_i \mathbf{1}(\gamma_5) d_j)\left(\bar{\ell}_\alpha P_L \nu_\beta\right),$$
$$[\epsilon_T(\mu)]^{ij}_{\alpha\beta}\left(\bar{u}_i \sigma^{\mu\nu} P_L d_j\right)\left(\bar{\ell}_\alpha \sigma_{\mu\nu} P_L \nu_\beta\right)\}$$

$$[\epsilon_{L(R)}]^{ij}_{\alpha\beta}, [\epsilon_{S(P)}]^{ij}_{\alpha\beta}, [\epsilon_T]^{ij}_{\alpha\beta}$$

$$\epsilon^s_{\alpha\beta}, \epsilon^d_{\alpha\beta}$$

Results: Current experiments

YD, H-L. Li, J. Tang, S. Vihonen, J-H. Yu, JHEP 03(2021) 019



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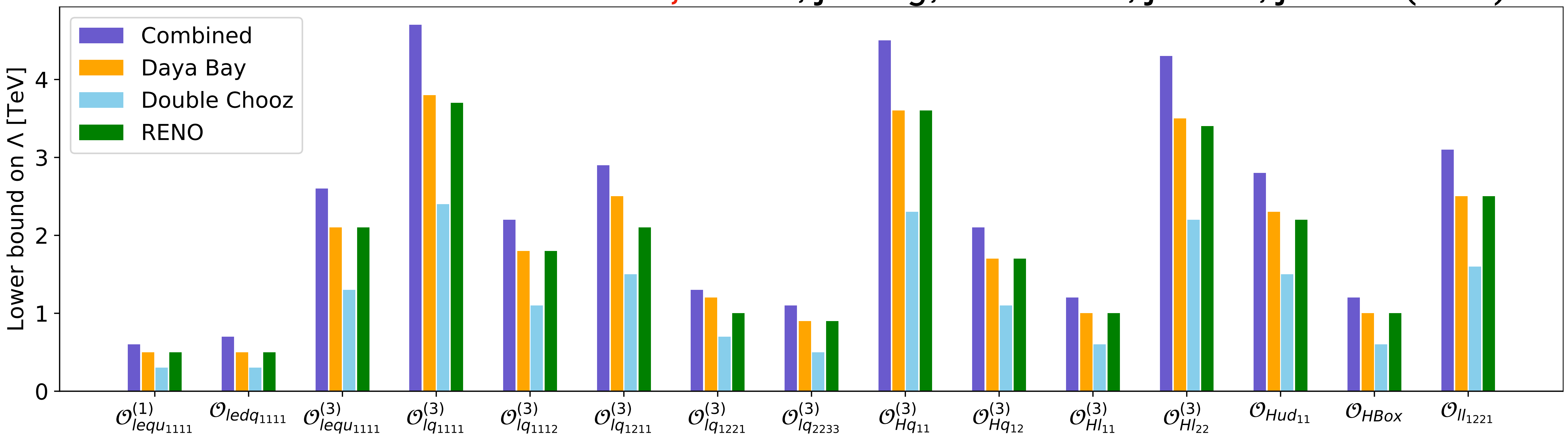

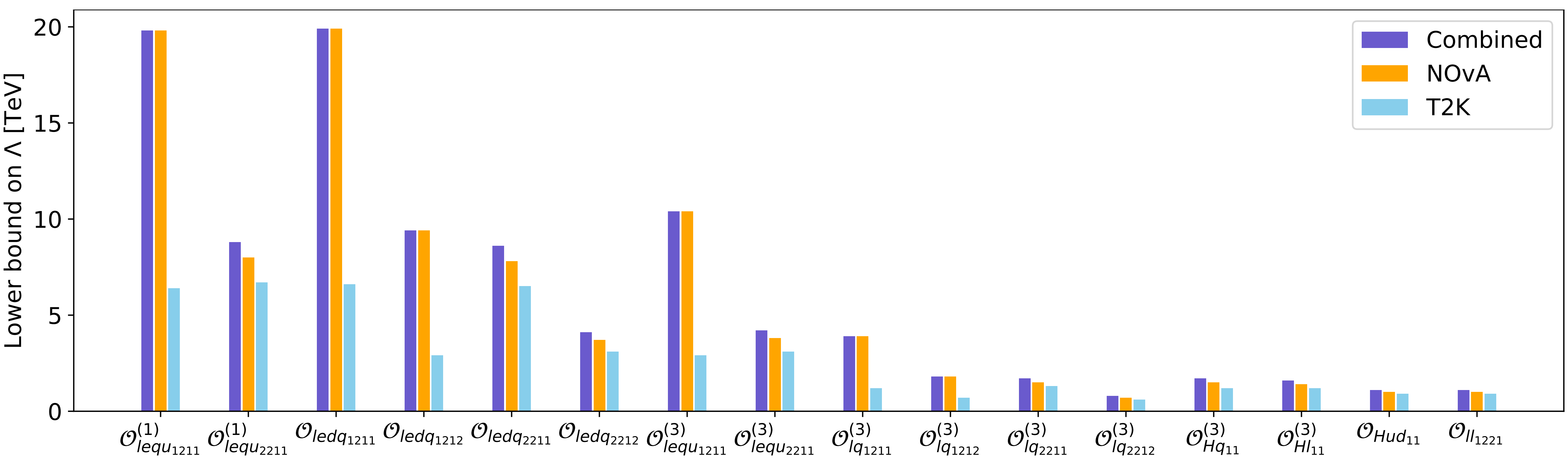

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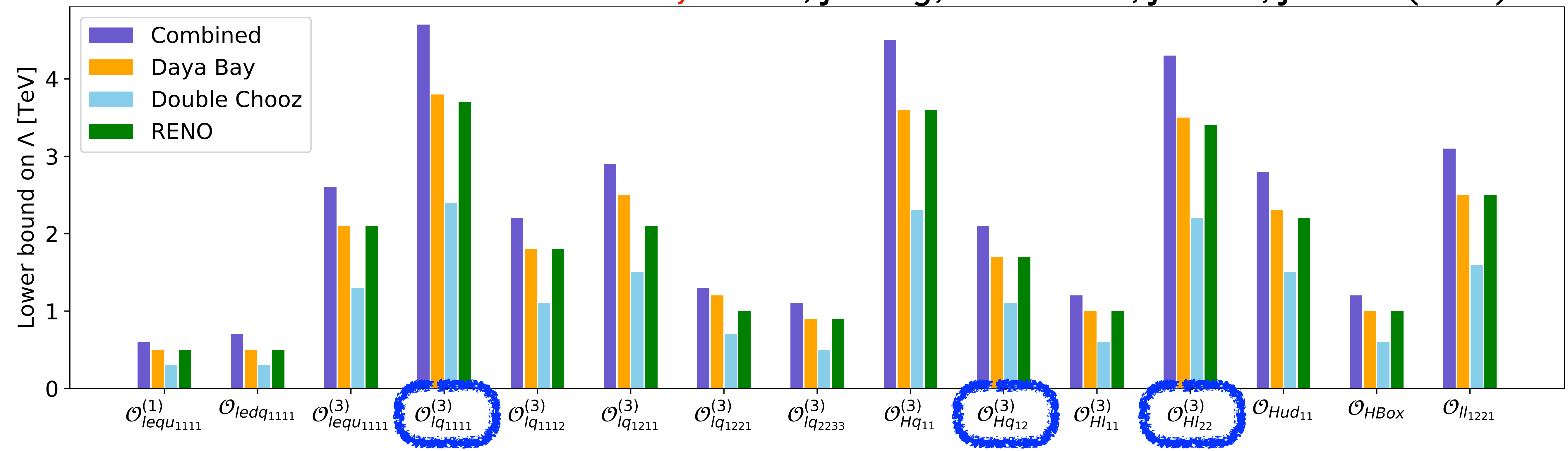

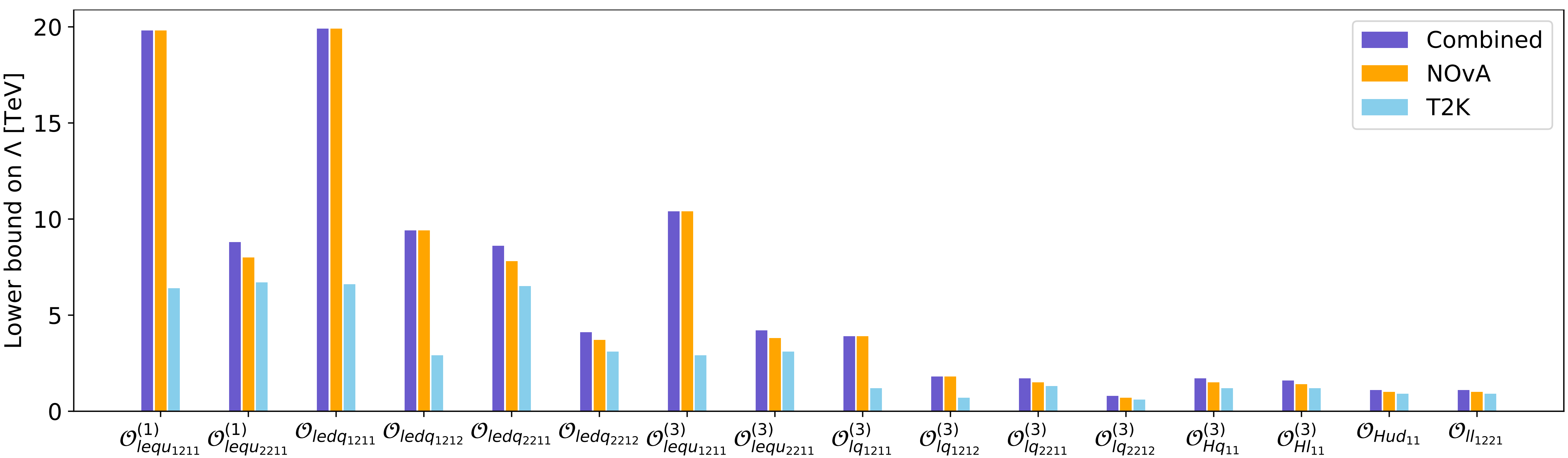

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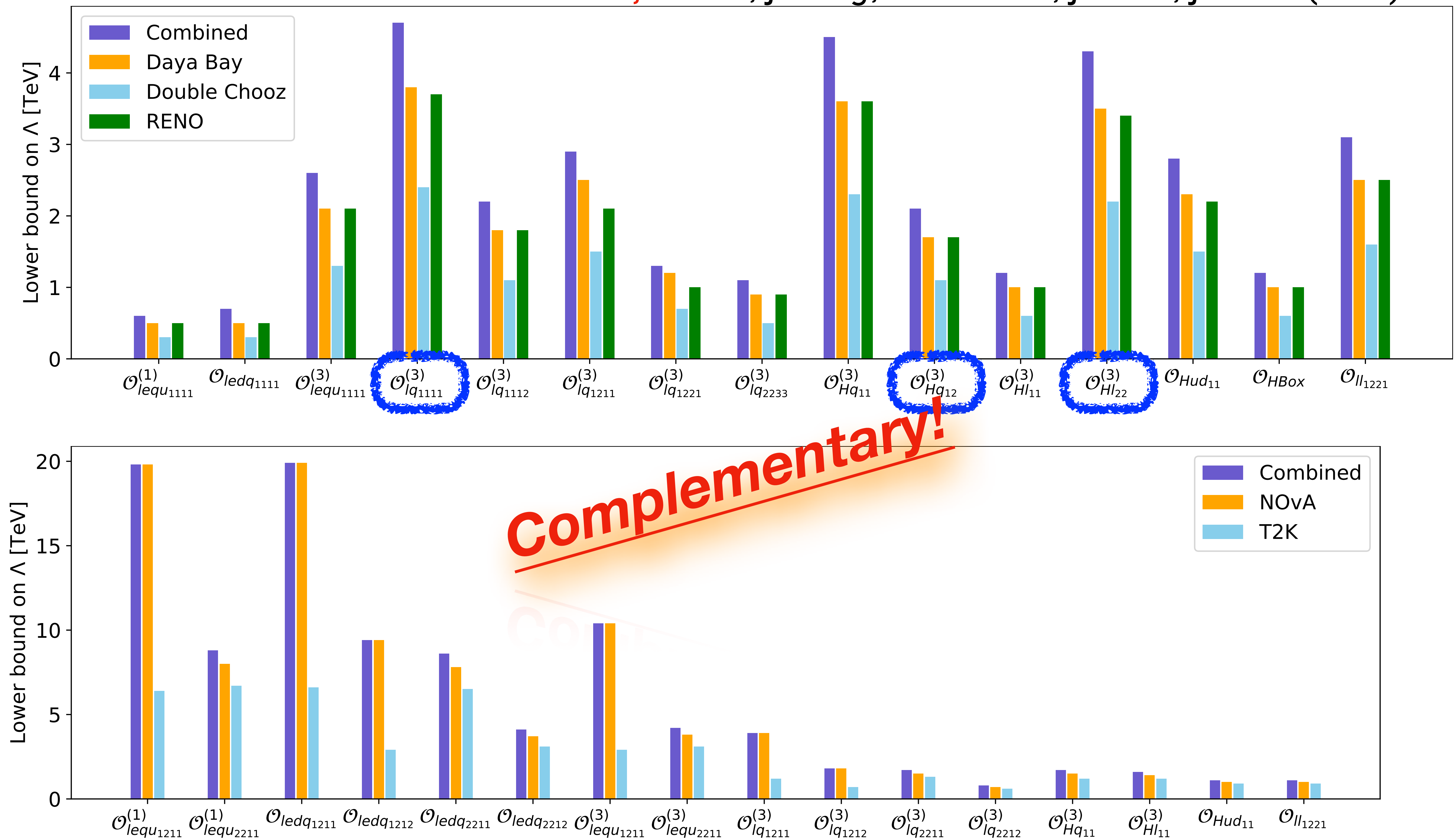
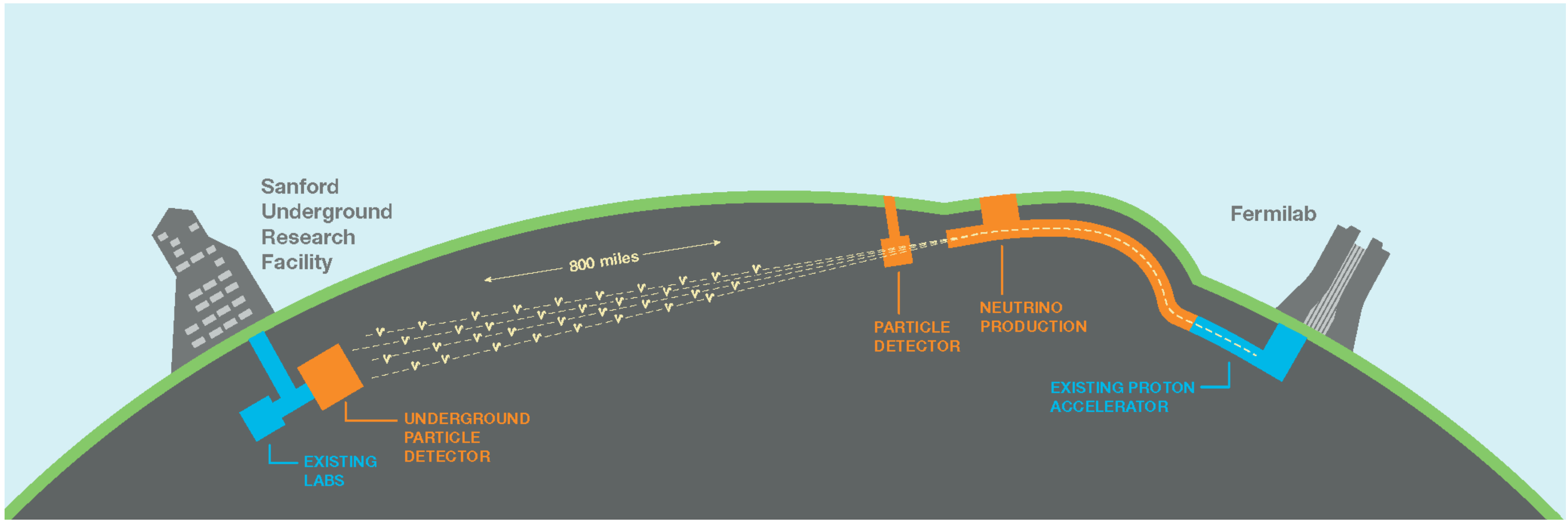
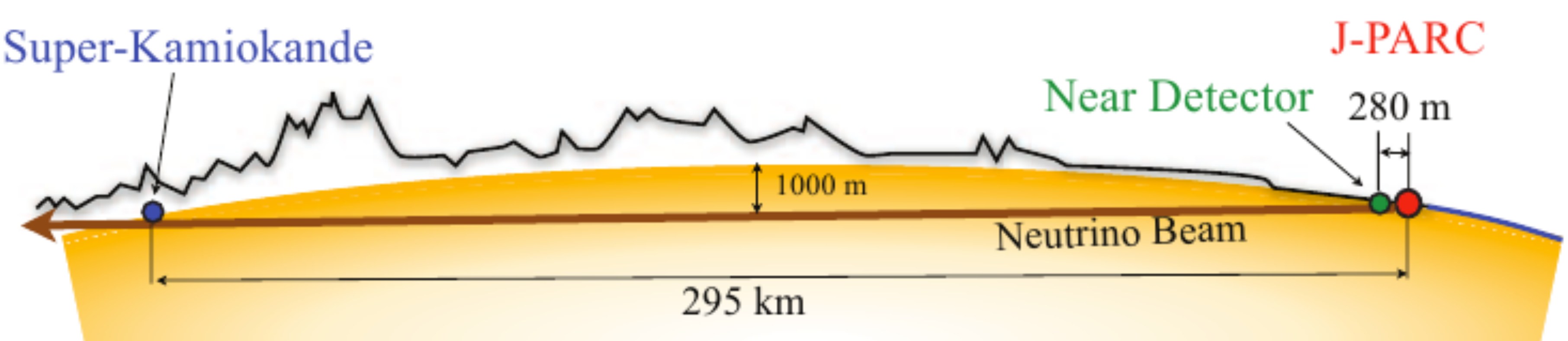


Results: Future experiments

Very long baseline neutrino experiments





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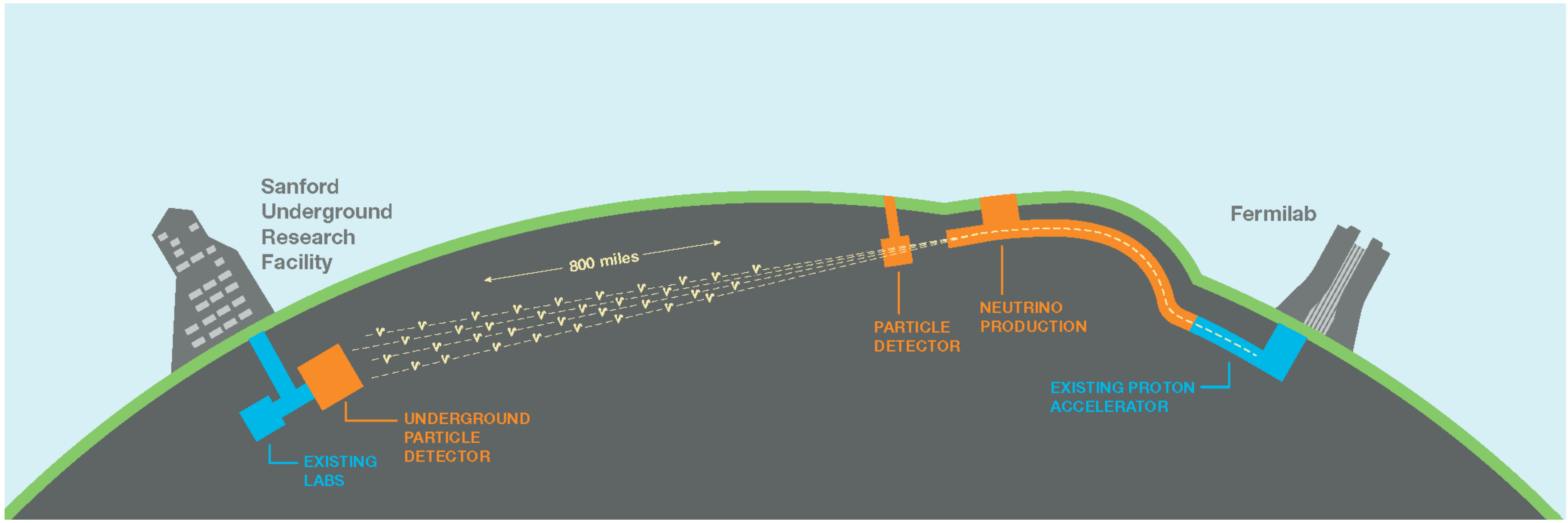

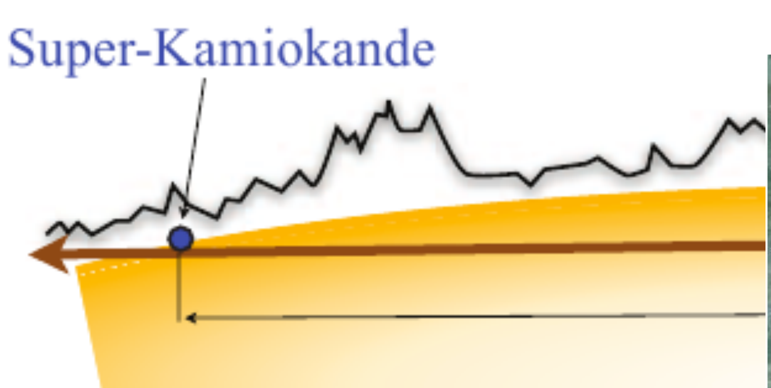

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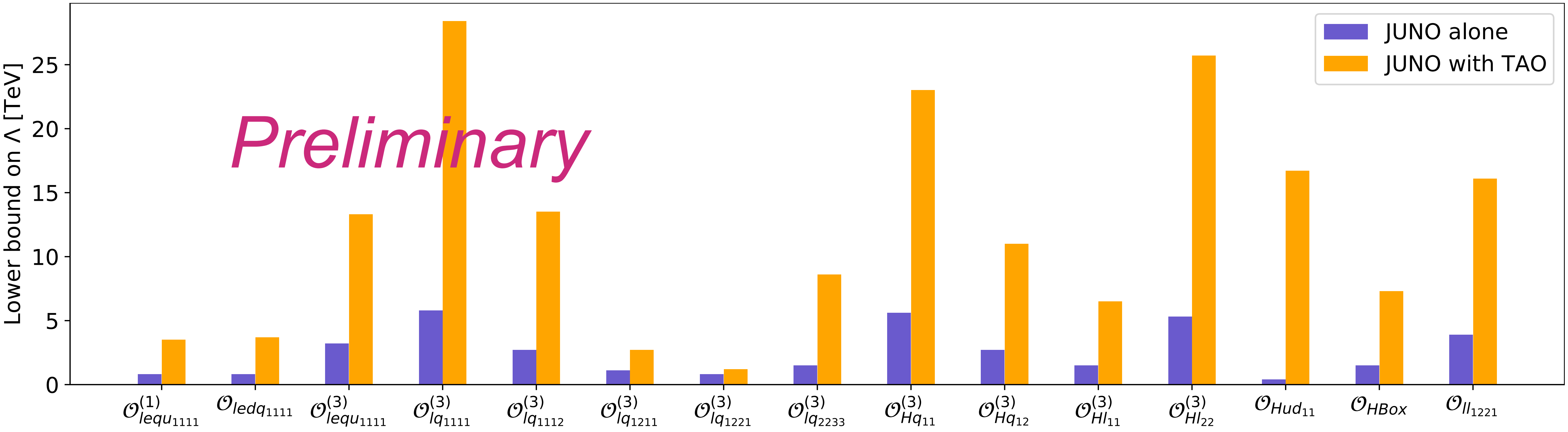
YD, H-L. Li, J. Tang, S. Vihonen, J-H. Yu, arXiv:2106.XXXXX



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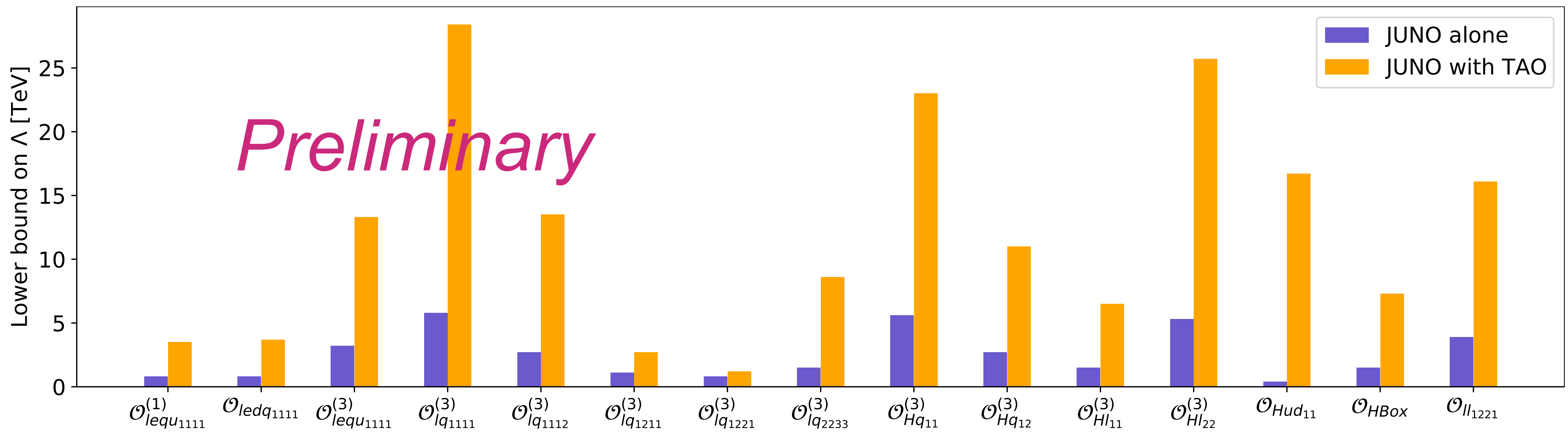
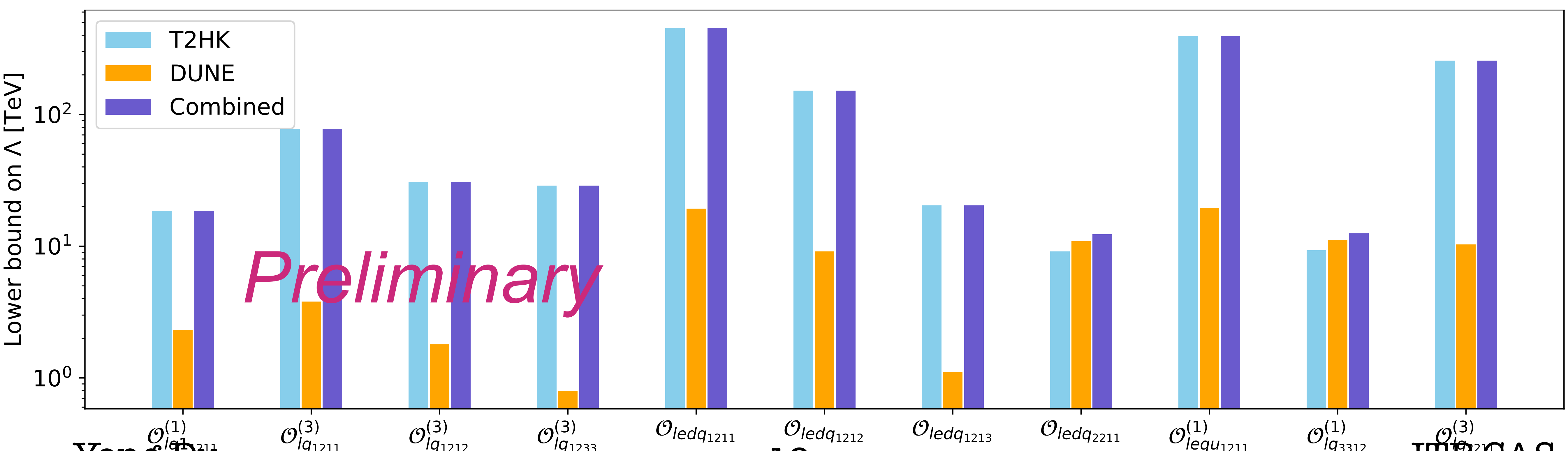
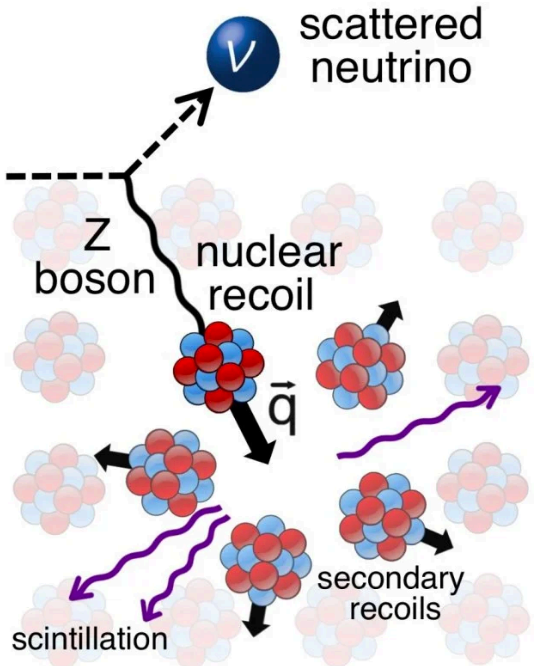


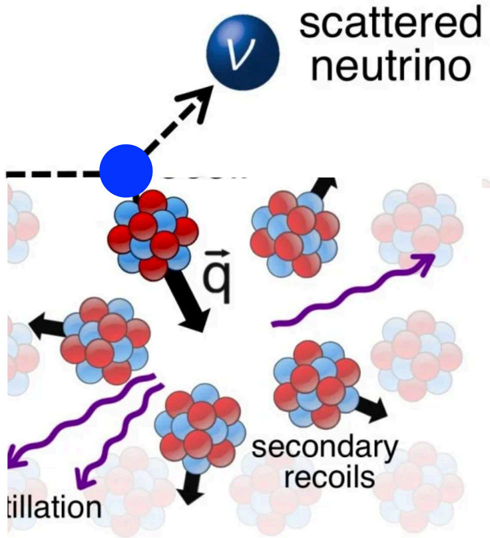


NC NSIs: CEvNS

Science 357 (2017)
Phys.Rev.Lett. 126 (2021) 1, 012002

$$\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^{f,P} \left(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta\right) \left(\bar{f}\gamma^\mu P f\right)$$





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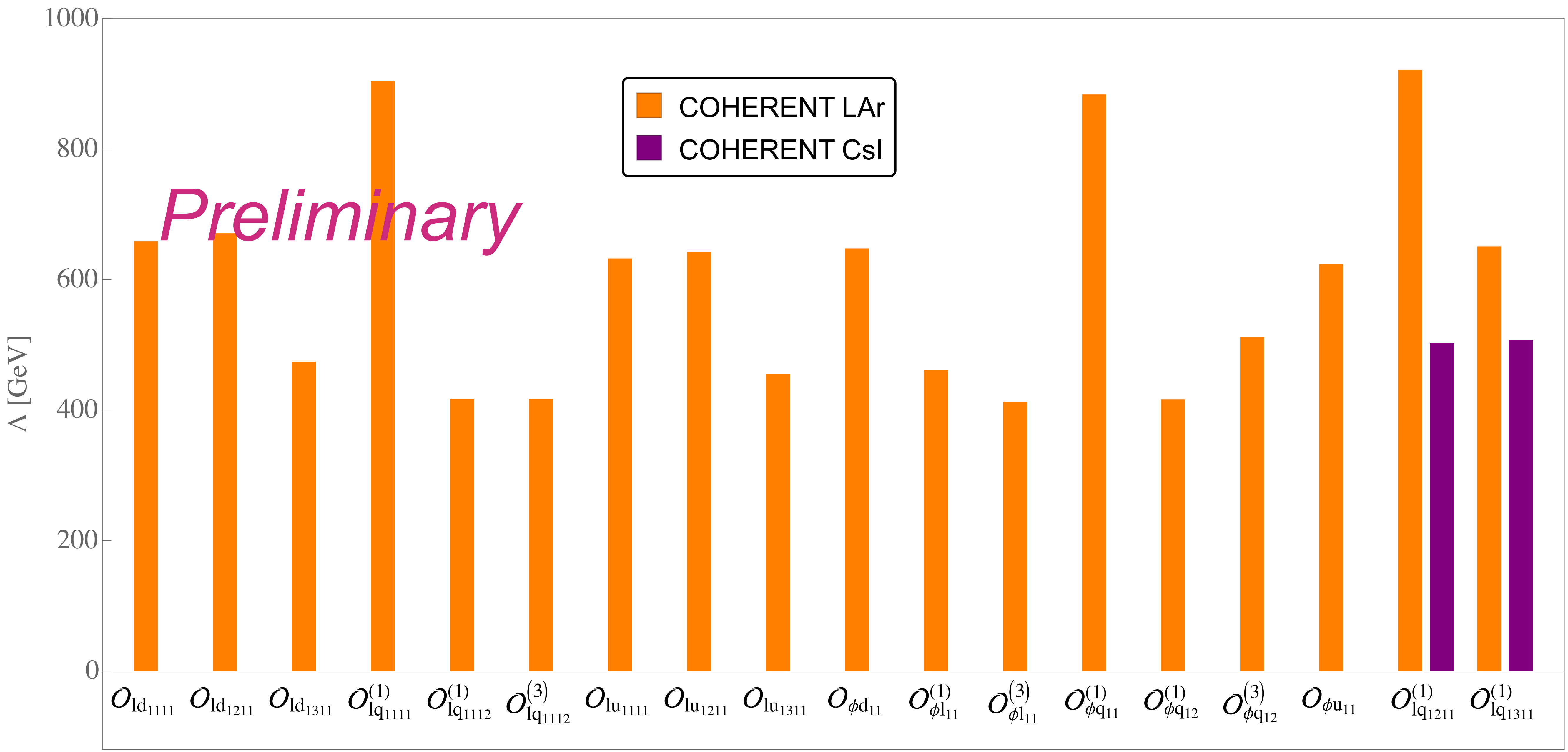
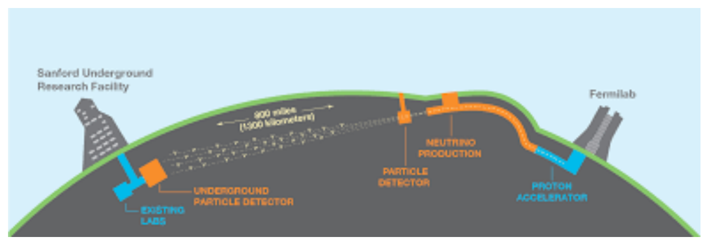
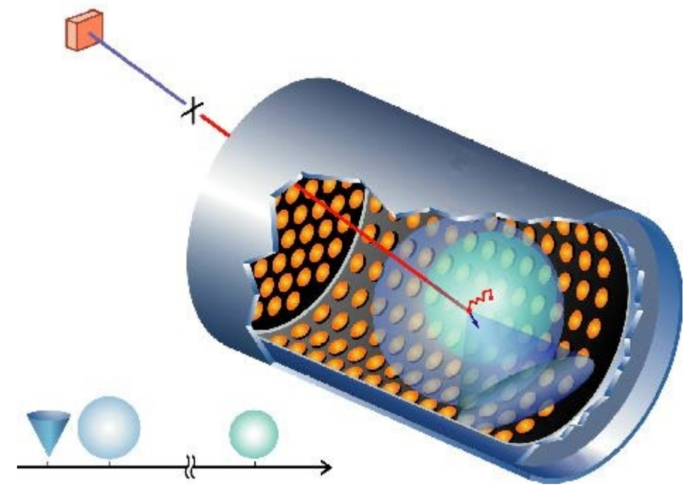


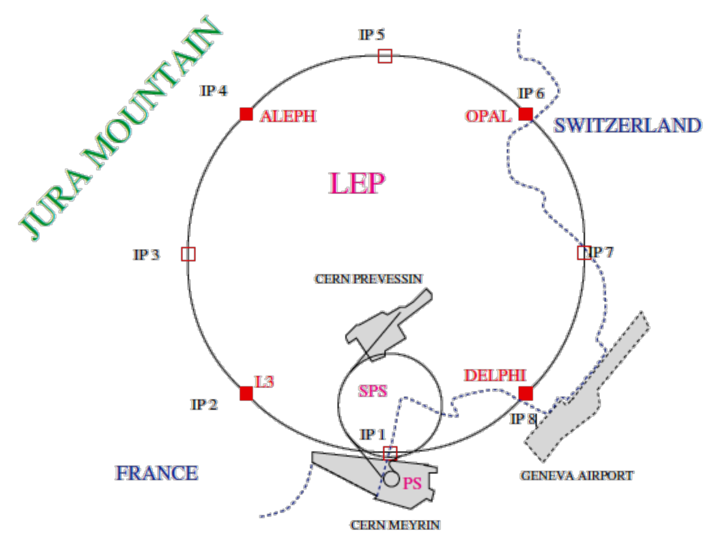
NC NSIs: cosmology

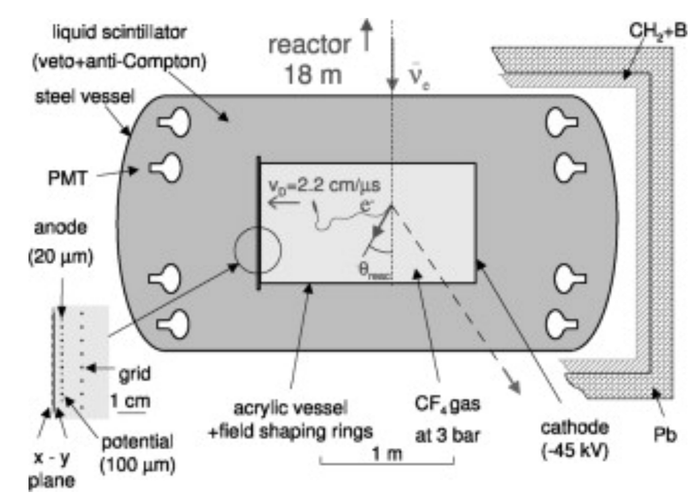
$$\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^{f,P} \left(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta\right)\left(\bar{f}\gamma^\mu P f\right)$$

Internal – Wiki









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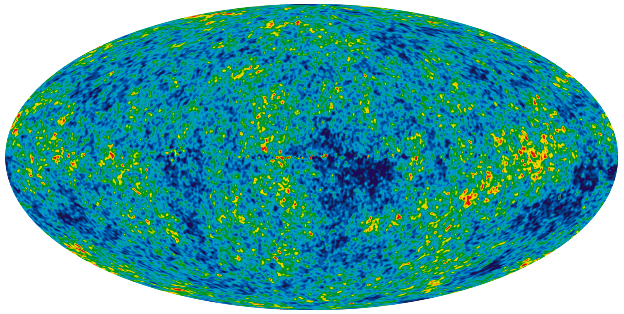

$$\rho_R = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\mathrm{eff}}\right]\rho_\gamma$$

NC NSIs: cosmology

Q: How NC NSIs affect neutrino decoupling?

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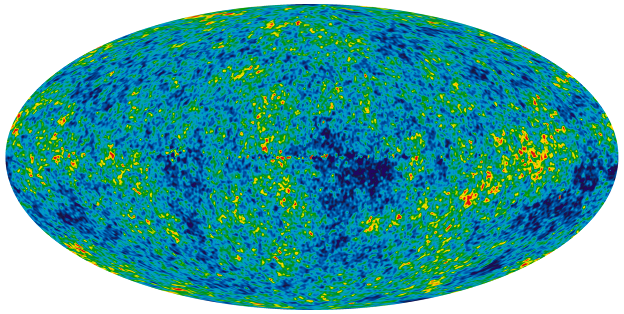

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NC NSIs: cosmology

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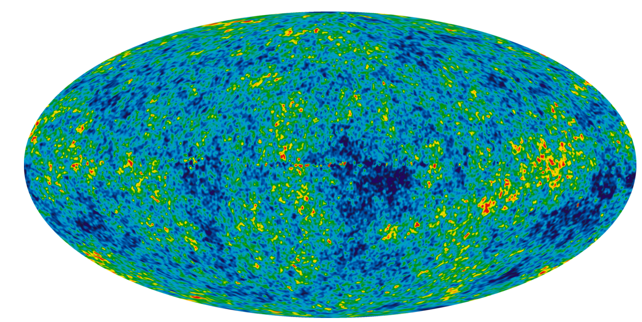
YD, J-H. Yu, arXiv: 2101.10475

Majoron model

U(1)' model

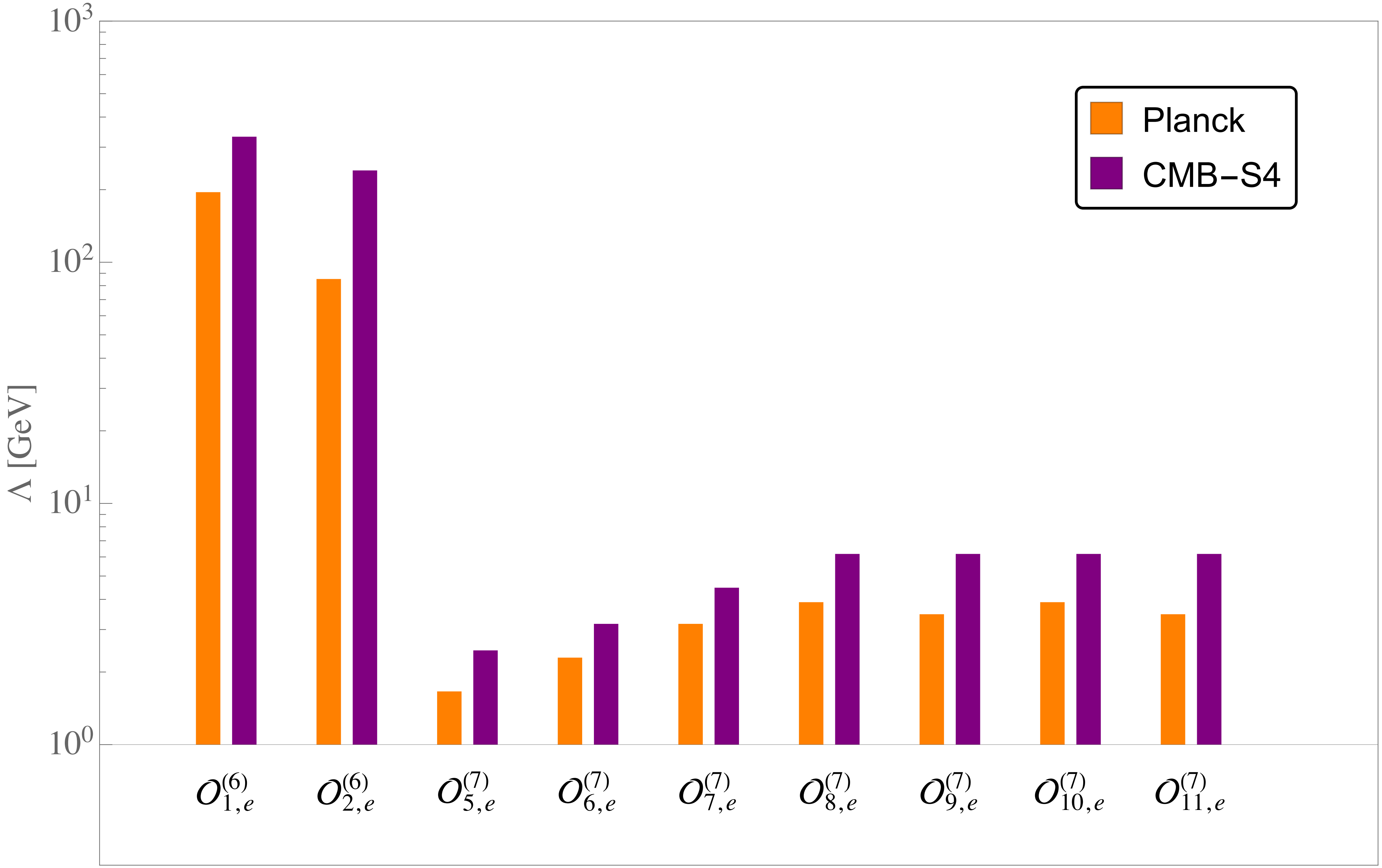
Dimensions	Operators	Wilson coefficients
dimension-5	$\mathcal{O}_1^{(5)} = \frac{e}{8\pi^2}\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right) F_{\mu\nu}$	$C_1^{(5)}$
dimension-6	$\mathcal{O}_{1,f}^{(6)} = \left(\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu f\right)$	$C_{1,f}^{(6)}$
	$\mathcal{O}_{2,f}^{(6)} = \left(\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu \gamma_5 f\right)$	$C_{2,f}^{(6)}$
	$\mathcal{O}_3^{(6)} = \left(\bar{\nu}_\beta P_L \nu_\alpha\right)\left(\bar{\nu}_{\beta'} P_L \nu_{\alpha'}\right)^\clubsuit$	$C_3^{(6)}$
	$\mathcal{O}_4^{(6)} = \left(\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha\right)\left(\bar{\nu}_{\beta'} \gamma_\mu P_L \nu_{\alpha'}\right)^\clubsuit$	$C_4^{(6)}$
	$\mathcal{O}_5^{(6)} = \left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{\nu}_{\beta'} \sigma^{\mu\nu} P_L \nu_{\alpha'}\right)^\clubsuit$	$C_5^{(6)}$
dimension-7	$\mathcal{O}_1^{(7)} = \frac{\alpha}{12\pi}\left(\bar{\nu}_\beta P_L \nu_\alpha\right) F^{\mu\nu} F_{\mu\nu}$	$C_1^{(7)}$
	$\mathcal{O}_2^{(7)} = \frac{\alpha}{8\pi}\left(\bar{\nu}_\beta P_L \nu_\alpha\right) F^{\mu\nu} \widetilde{F}_{\mu\nu}$	$C_2^{(7)}$
	$\mathcal{O}_{5,f}^{(7)} = m_f\left(\bar{\nu}_\beta P_L \nu_\alpha\right)\left(\bar{f} f\right)$	$C_{5,f}^{(7)}$
	$\mathcal{O}_{6,f}^{(7)} = m_f\left(\bar{\nu}_\beta P_L \nu_\alpha\right)\left(\bar{f} i\gamma_5 f\right)$	$C_{6,f}^{(7)}$
	$\mathcal{O}_{7,f}^{(7)} = m_f\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\sigma_{\mu\nu} f\right)$	$C_{7,f}^{(7)}$
	$\mathcal{O}_{8,f}^{(7)} = \left(\bar{\nu}_\beta i \overleftrightarrow{\partial}_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu f\right)$	$C_{8,f}^{(7)}$
	$\mathcal{O}_{9,f}^{(7)} = \left(\bar{\nu}_\beta i \overleftrightarrow{\partial}_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu \gamma_5 f\right)$	$C_{9,f}^{(7)}$
	$\mathcal{O}_{10,f}^{(7)} = \partial_\mu\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\gamma_\nu f\right)$	$C_{10,f}^{(7)}$
	$\mathcal{O}_{11,f}^{(7)} = \partial_\mu\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\gamma_\nu \gamma_5 f\right)$	$C_{11,f}^{(7)}$



$$\rho_R = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\text{eff}}\right]\rho_\gamma$$

Results: NC NSIs

YD, J-H. Yu, arXiv: 2101.10475



Results: NC NSIs comparison

YD, J-H. Yu, arXiv: 2101.10475

$$\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}G_F \sum_{\alpha\beta,f,P} \epsilon_{\alpha\beta}^{f,P} \left(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta\right)\left(\bar{f}\gamma^\mu P f\right)$$

ϵ's	[103]	[97]	[82]	[83]	[84]	[85]	[90]	[98]	[35]	This work	
										Planck	CMB-S4
$\epsilon_{ee}^{e,L}$	[-0.010, 2.039]	[-1.53, 0.38]	[-0.07, 0.1]	[-0.05, 0.12]	[-0.03, 0.08]	[-0.036, 0.063]	[-0.017, 0.027] [-0.003, 0.003]	[-0.08, 0.08]	[-0.185, 0.380] [-0.130, 0.185]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon_{e\mu}^{e,L}$	[-0.179, 0.146]	[-0.84, 0.84]	-	-	[-0.13, 0.13]	-	[-0.152, 0.152] [-0.055,0.055]	[-0.33, 0.35]	[-0.025, 0.052] [-0.017, 0.040]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon_{e\tau}^{e,L}$	[-0.860, 0.350]	[-0.84, 0.84]	[-0.4, 0.4]	[-0.44, 0.44]	[-0.33, 0.33]	-	[-0.152, 0.152] [-0.055,0.055]	[-0.33, 0.35]	[-0.055, 0.023] [-0.042, 0.012]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon_{\mu\mu}^{e,L}$	[-0.364, 1.387]	-	[-0.03,0.03]	-	[-0.03, 0.03]	-	[-0.040, 0.04] [-0.010,0.010]	-	[-0.290, 0.390] [-0.192, 0.240]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon_{\mu\tau}^{e,L}$	[-0.035, 0.028]	-	[-0.1,0.1]	-	[-0.1, 0.1]	-	-	-	[-0.015, 0.013] [-0.010, 0.010]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon_{\tau\tau}^{e,L}$	[-0.350, 1.400]	-	[-0.5,0.5]	-	[-0.46, 0.24]	[-0.16 , 0.110] [0.41, 0.66]	[-0.040, 0.04] [-0.010,0.010]	-	[-0.360, 0.145] [-0.120, 0.095]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon_{ee}^{e,R}$	[-0.010, 2.039]	[-0.07, 0.08]	[-1, 0.5]	[-0.04, 0.14]	[0.004, 0.151]	[-0.27, 0.59]	[-0.33 , 0.25] [-0.07, 0.07]	[-0.04, 0.06]	[-0.185, 0.380] [-0.130, 0.185]	[-1.6, 1.44]	[-0.39, 0.31]
$\epsilon_{e\mu}^{e,R}$	[-0.179, 0.146]	[-0.19, 0.19]	-	-	[-0.13, 0.13]	-	[-0.236, 0.236] [-0.08, 0.08]	[-0.15, 0.16]	[-0.025, 0.052] [-0.017, 0.040]	[-1.6, 1.44]	[-0.39, 0.31]
$\epsilon_{e\tau}^{e,R}$	[-0.860, 0.350]	[-0.19, 0.19]	[-0.7, 0.7]	[-0.27, 0.27]	[-0.05 , 0.05] [-0.28, 0.28]	-	[-0.236, 0.236] [-0.08, 0.08]	[-0.15, 0.16]	[-0.055, 0.023] [-0.042, 0.012]	[-1.6, 1.44]	[-0.39, 0.31]
$\epsilon_{\mu\mu}^{e,R}$	[-0.364, 1.387]	-	[-0.03,0.03]	-	[-0.03, 0.03]	-	[-0.10 , 0.12] [-0.006, 0.006]	-	[-0.290, 0.390] [-0.192, 0.240]	[-1.6, 1.44]	[-0.39, 0.31]
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Results: NC NSIs comparison

YD, J-H. Yu, arXiv: 2101.10475

$$\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}G_F \sum_{\alpha\beta,f,P} \epsilon_{\alpha\beta}^{f,P} \left(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta\right) \left(\bar{f}\gamma^\mu P f\right)$$

ϵ's	[103]	[97]	[82]	[83]	[84]	[85]	[90]	[98]	[35]	This work	
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$\epsilon^{e,L}_{e\mu}$	[-0.179, 0.146]	[-0.84, 0.84]	-	-	[-0.13, 0.13]	-	[-0.152, 0.152] [-0.055,0.055]	[-0.33, 0.35]	[-0.025, 0.052] [-0.017, 0.040]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon^{e,L}_{e\tau}$	[-0.860, 0.350]	[-0.84, 0.84]	[-0.4, 0.4]	[-0.44, 0.44]	[-0.33, 0.33]	-	[-0.152, 0.152] [-0.055,0.055]	[-0.33, 0.35]	[-0.055, 0.023] [-0.042, 0.012]	[-1.6, 1.44]	[-0.61, 0.46]
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$\epsilon^{e,L}_{\tau\tau}$	[-0.350, 1.400]	-	[-0.5,0.5]	-	[-0.46, 0.24]	[-0.16 , 0.110] [0.41, 0.66]	[-0.040, 0.04] [-0.010,0.010]	-	[-0.360, 0.145] [-0.120, 0.095]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon^{e,R}_{ee}$	[-0.010, 2.039]	[-0.07, 0.08]	[-1, 0.5]	[-0.04, 0.14]	[0.004, 0.151]	[-0.27, 0.59]	[-0.33 , 0.25] [-0.07, 0.07]	[-0.04, 0.06]	[-0.185, 0.380] [-0.130, 0.185]	[-1.6, 1.44]	[-0.39, 0.31]
$\epsilon^{e,R}_{e\mu}$	[-0.179, 0.146]	[-0.19, 0.19]	-	-	[-0.13, 0.13]	-	[-0.236, 0.236] [-0.08, 0.08]	[-0.15, 0.16]	[-0.025, 0.052] [-0.017, 0.040]	[-1.6, 1.44]	[-0.39, 0.31]
$\epsilon^{e,R}_{e\tau}$	[-0.860, 0.350]	[-0.19, 0.19]	[-0.7, 0.7]	[-0.27, 0.27]	[-0.05 , 0.05] [-0.28, 0.28]	-	[-0.236, 0.236] [-0.08, 0.08]	[-0.15, 0.16]	[-0.055, 0.023] [-0.042, 0.012]	[-1.6, 1.44]	[-0.39, 0.31]
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$\epsilon^{e,R}_{\mu\tau}$	[-0.035, 0.028]	-	[-0.1,0.1]	-	[-0.1, 0.1]	-	-	-	[-0.015, 0.013] [-0.010, 0.010]	[-1.6, 1.44]	[-0.39, 0.31]
$\epsilon^{e,R}_{\tau\tau}$	[-0.350, 1.400]	-	[-0.5,0.5]	-	[-0.25, 0.43]	[-1.05, 0.31]	[-0.10 , 0.12] [-0.006, 0.006]	-	[-0.360, 0.145] [-0.120, 0.095]	[-1.6, 1.44]	[-0.39, 0.31]

Complementary!

Summary

We investigate charge- and neutral-current neutrino NSIs in the EFT framework.

- For CC NSIs, we find reactor (Daya Bay, Double Chooze, RENO) and long baseline (T2K, NOvA) neutrino experiments are complementary, the latter are sensitive to new physics already at the ~20TeV scale.

- For future long baseline neutrino experiments (JUNO, DUNE, T2HK), would be sensitive to new physics at O(100TeV) for certain operators.

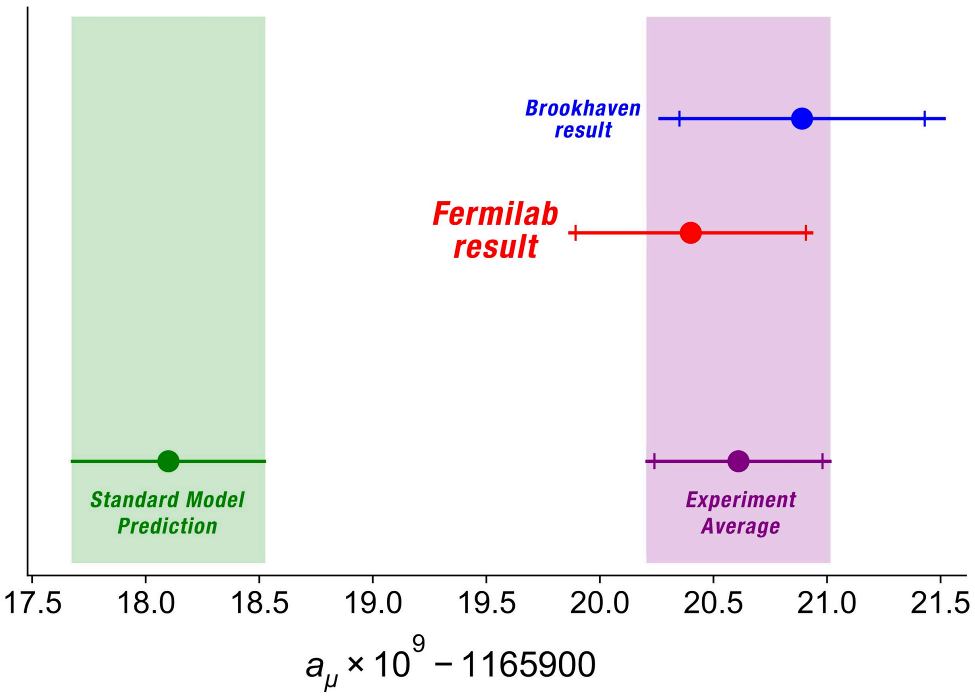
- For NC NSIs up to dim-7, constraints from precision measurements of Neff (Planck, CMB-S4) are complementary to other type of neutrino experiments (COHERENT, collider, solar and reactor neutrino experiments, DUNE etc).

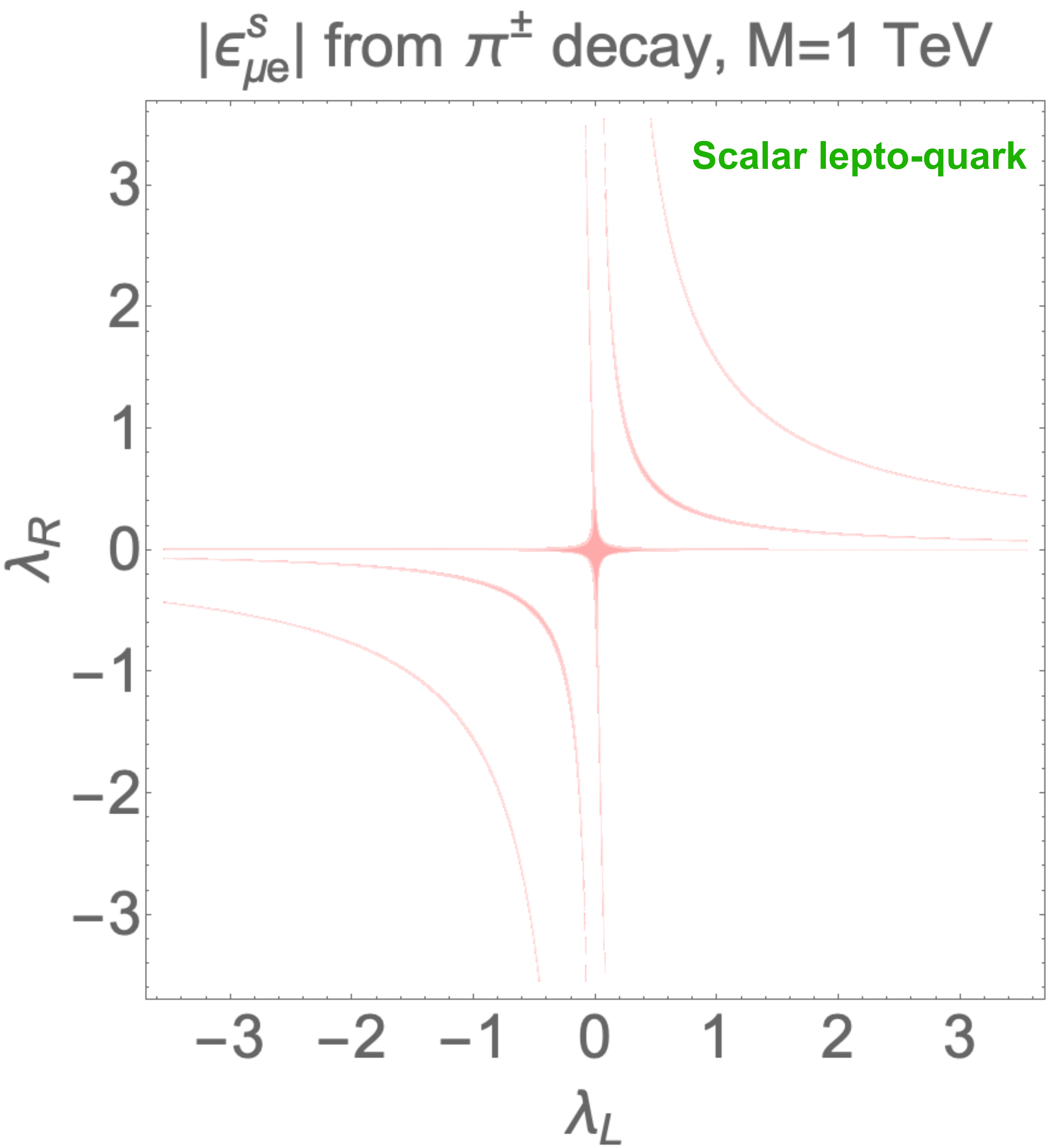
Back up

Overview

YD, H-L. Li, J. Tang, S. Vihonen, J-H. Yu, JHEP 03(2021) 019

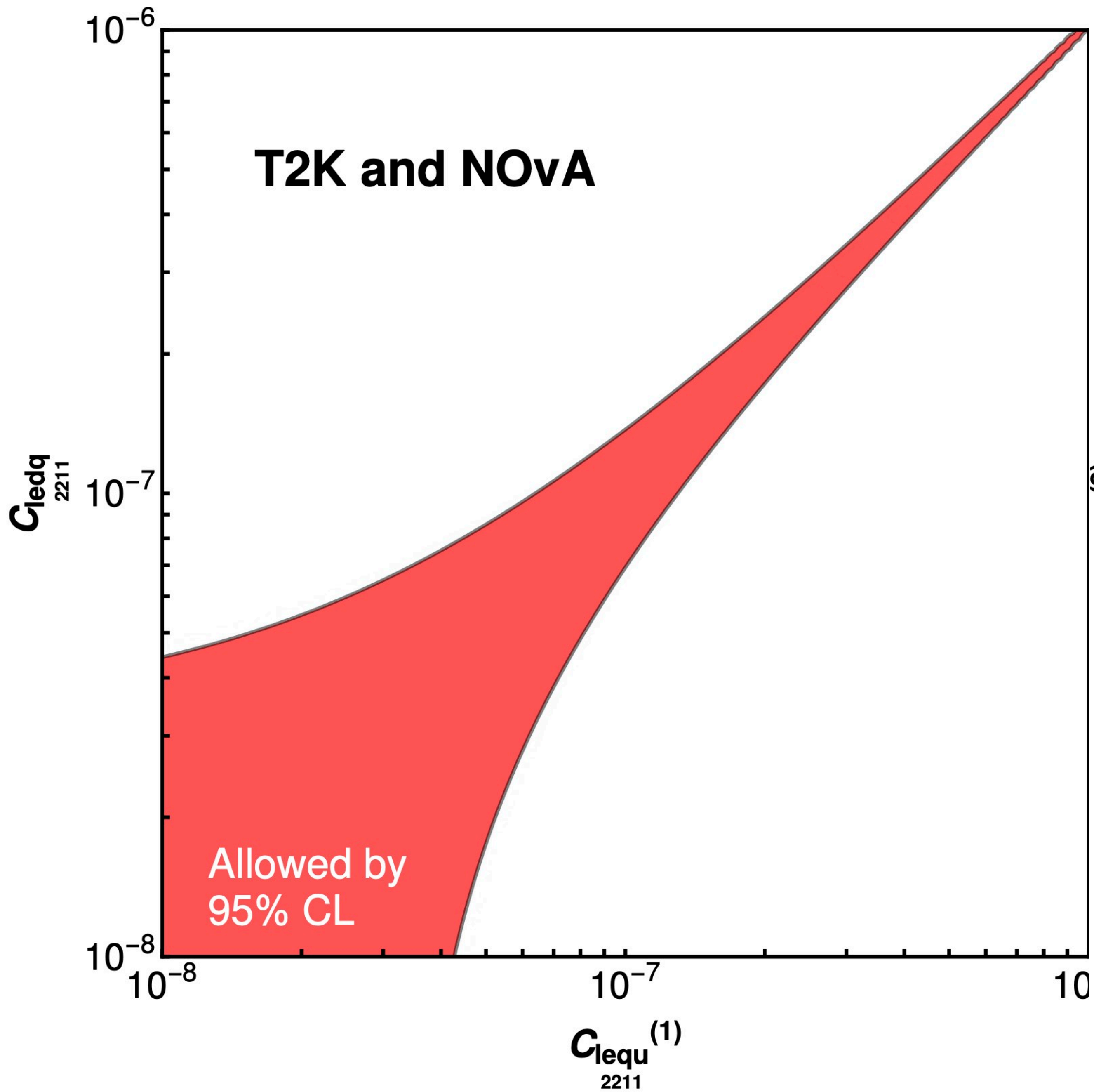
$$\mathcal{L}_{\rm LQ} = |D_\mu S|^2 - M_1^2|S|^2 - \lambda_{H1}|H|^2|S|^2 - \frac{c}{2}|S|^4 + \left((\lambda^L)_{i\alpha}\bar{q}_i^c\epsilon\ell_\alpha + (\lambda^R)_{i\alpha}\bar{u}_i^c e_\alpha\right)S_1 + \text{h.c.}$$

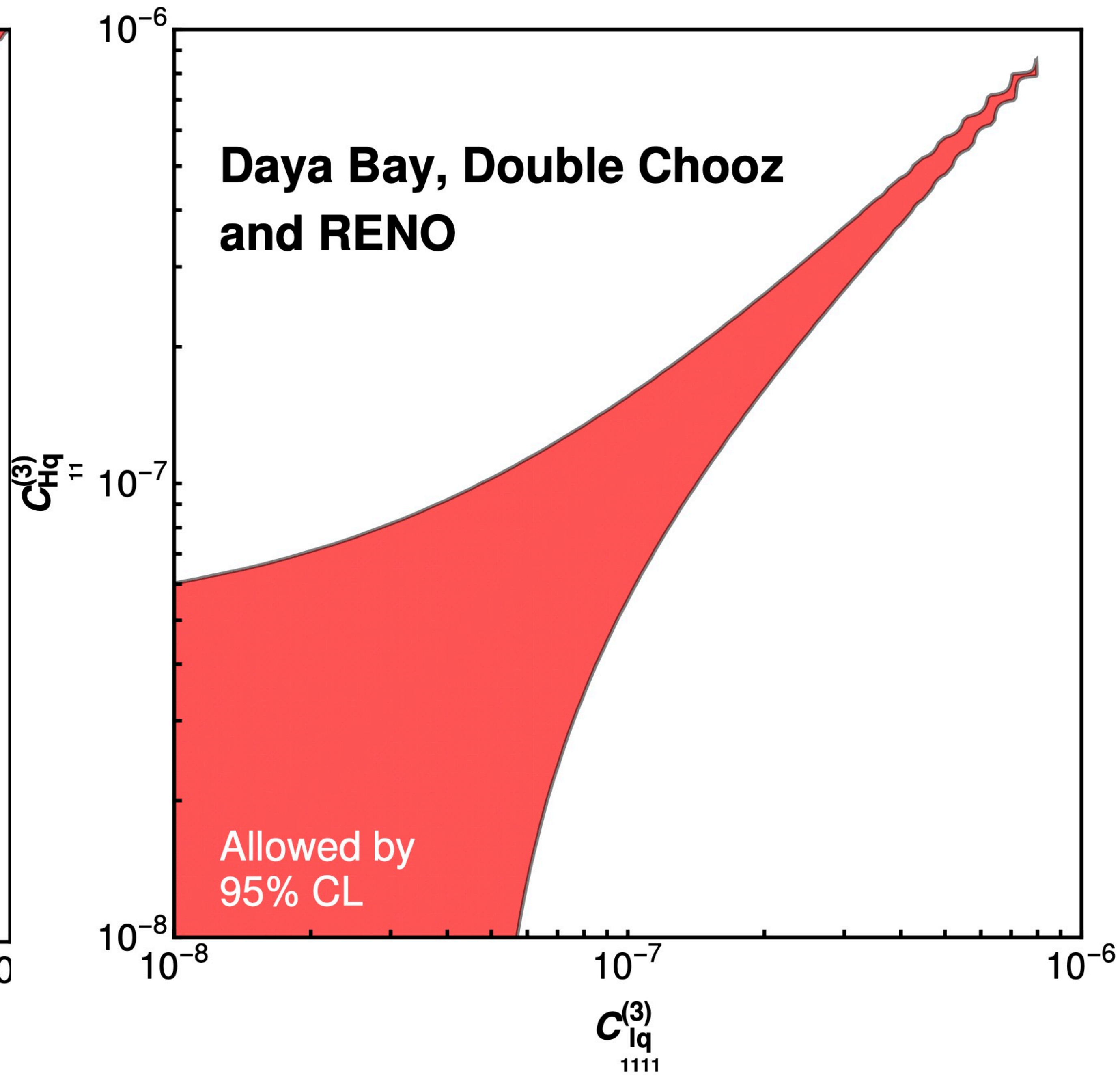




Multiple operators

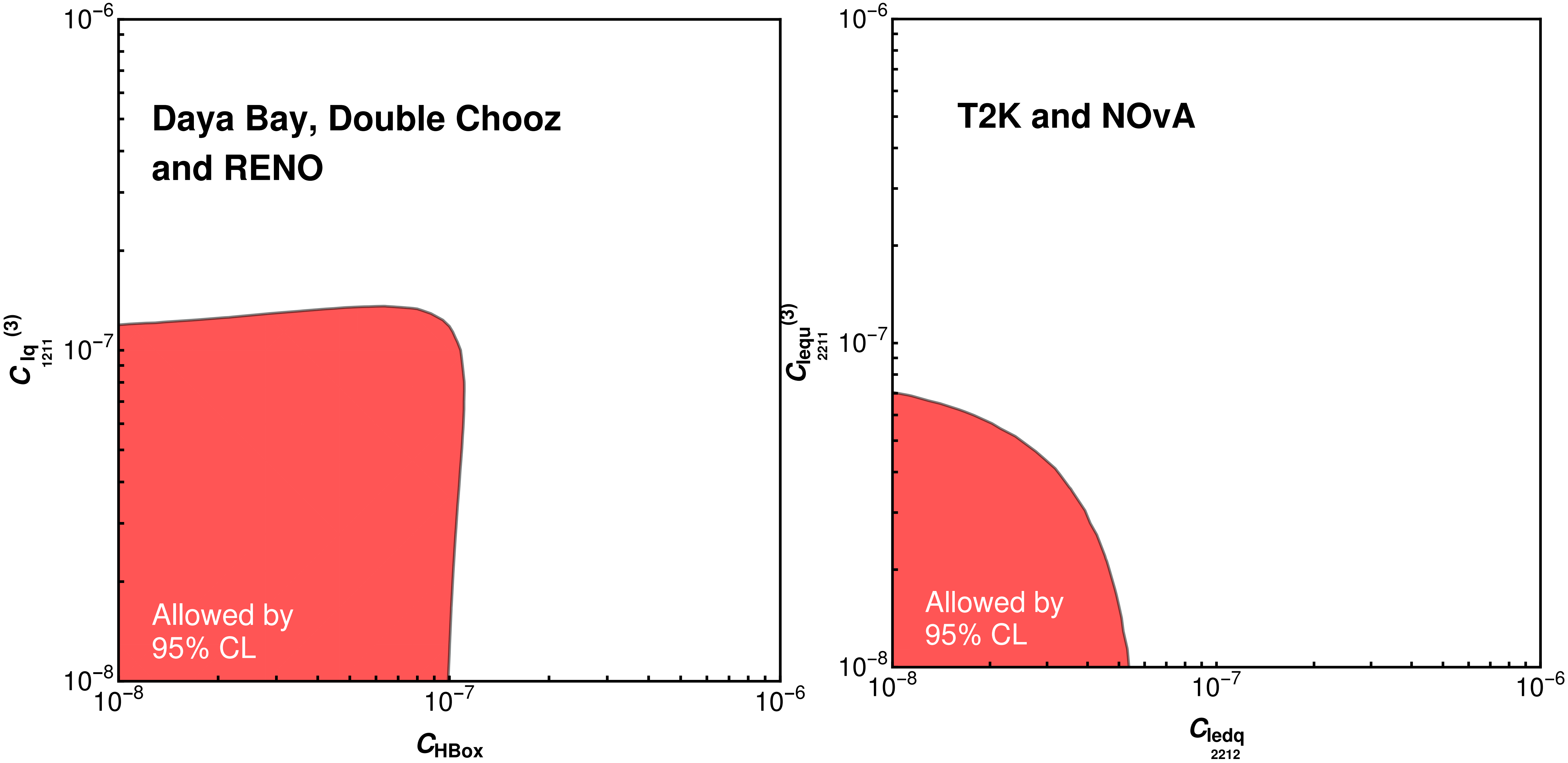
YD, H-L. Li, J. Tang, S. Vihonen, J-H. Yu, JHEP 03(2021) 019





Multiple operators

YD, H-L. Li, J. Tang, S. Vihonen, J-H. Yu, JHEP 03(2021) 019



NC NSIs: Future experiments

Experiment	T2HK	DUNE	JUNO
Type	superbeam	superbeam	reactor
Source location	Japan	USA	China
Beam/reactor power	1.3 MW	1.07 MW	36 GW_{th}
Running time	2.5+7.5 yrs	3.5+3.5 yrs	6 yrs
Detector technology	W.C	L.Ar.	L.Sc.
Fiducial mass (far)	187 kt (374 kt)	40 kt	20 kt
Fiducial mass (near)	1.529 t	67.2 t	2.5 t
Baseline length (far)	295 km	1300 km	53 km
Baseline length (near)	280 m	547 m	30 m
Off-axis angle	2.5°	0°	0°
References	Ref. [1]	Ref. [46]	Ref. [3]

NC NSIs: Future experiments

Process	NSI parameter	Constraint	Experiment(s)
Pion decay	$\lvert\epsilon^s_{\mu e}\rvert$	9×10^{-6}	T2HK, DUNE
	$\lvert\epsilon^s_{\mu\mu}\rvert$	2×10^{-2}	
	$\lvert\epsilon^s_{\mu\tau}\rvert$	5×10^{-2}	
Propagation in matter	$(\epsilon^m_{ee}-\epsilon^m_{\mu\mu})$	(-0.3, 0.3)	T2HK, DUNE
	$(\epsilon^m_{\tau\tau}-\epsilon^m_{\mu\mu})$	(-0.2, 0.2)	
	$\lvert\epsilon^m_{e\mu}\rvert$	2×10^{-2}	
	$\lvert\epsilon^m_{e\tau}\rvert$	5×10^{-2}	
	$\lvert\epsilon^m_{\mu\tau}\rvert$	2×10^{-2}	
Beta decay	$\lvert\epsilon^s_{ee}\rvert$	4×10^{-4}	JUNO
	$\lvert\epsilon^s_{e\mu}\rvert$	5×10^{-3}	
	$\lvert\epsilon^s_{e\tau}\rvert$	4×10^{-3}	
Inverse beta decay	$\lvert\epsilon^d_{ee}\rvert$	3×10^{-4}	JUNO
	$\lvert\epsilon^d_{\mu e}\rvert$	6×10^{-3}	
	$\lvert\epsilon^d_{\tau e}\rvert$	5×10^{-3}	

Reactor vs LBL neutrino experiments

Reactor

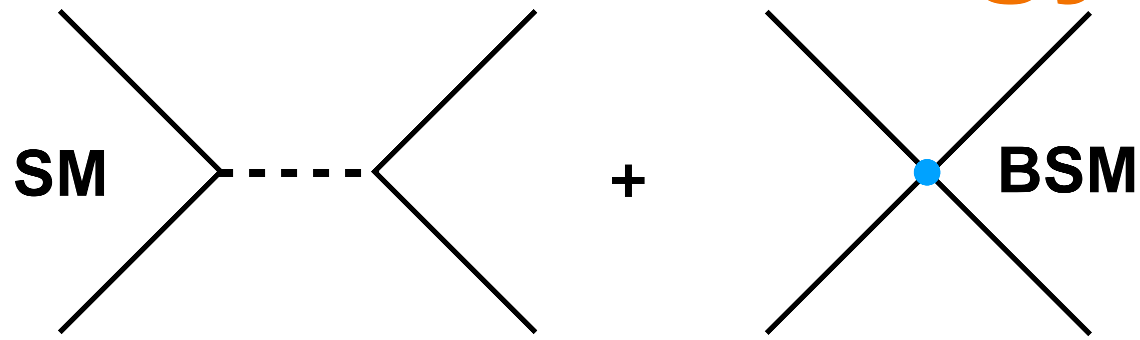
$$\epsilon^s_{e\beta} = \left[\epsilon_L - \epsilon_R - \frac{g_T}{g_A}\frac{m_e}{f_T(E_\nu)}\epsilon_T\right]^*_{e\beta}, \quad (\beta \text{ decay}) \tag{2.4}$$

$$\epsilon^d_{\beta e} = \left[\epsilon_L + \frac{1-3g_A^2}{1+3g_A^2}\epsilon_R - \frac{m_e}{E_\nu - \Delta}\left(\frac{g_S}{1+3g_A^2}\epsilon_S - \frac{3g_A g_T}{1+3g_A^2}\epsilon_T\right)\right]_{e\beta}, \quad (\text{inverse } \beta \text{ decay}) \tag{2.5}$$

LBL

$$\epsilon^s_{\mu\beta} = \left[\epsilon_L - \epsilon_R - \frac{m_\pi^2}{m_\mu(m_u + m_d)}\epsilon_P\right]^*_{\mu\beta}, \quad (\text{pion decay}) \tag{2.6}$$

NC NSIs: cosmology



$$\frac{dn}{dt} + 3Hn = \int g \frac{d^3p}{(2\pi)^3}\mathcal{C}[f],$$

$$\frac{d\rho}{dt} + 3H(\rho + p) = \int gE \frac{d^3p}{(2\pi)^3}\mathcal{C}[f]$$

Dimensions	Operators	Wilson coefficients
dimension-5	$\mathcal{O}_1^{(5)} = \frac{e}{8\pi^2}\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right) F_{\mu\nu}$	$C_1^{(5)}$
dimension-6	$\mathcal{O}_{1,f}^{(6)} = \left(\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu f\right)$	$C_{1,f}^{(6)}$
	$\mathcal{O}_{2,f}^{(6)} = \left(\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu \gamma_5 f\right)$	$C_{2,f}^{(6)}$
	$\mathcal{O}_3^{(6)} = \left(\bar{\nu}_\beta P_L \nu_\alpha\right)\left(\bar{\nu}_{\beta'} P_L \nu_{\alpha'}\right)^{\clubsuit}$	$C_3^{(6)}$
	$\mathcal{O}_4^{(6)} = \left(\bar{\nu}_\beta \gamma_\mu P_L \nu_\alpha\right)\left(\bar{\nu}_{\beta'} \gamma_\mu P_L \nu_{\alpha'}\right)^{\clubsuit}$	$C_4^{(6)}$
	$\mathcal{O}_5^{(6)} = \left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{\nu}_{\beta'} \sigma^{\mu\nu} P_L \nu_{\alpha'}\right)^{\clubsuit}$	$C_5^{(6)}$
dimension-7	$\mathcal{O}_1^{(7)} = \frac{\alpha}{12\pi}\left(\bar{\nu}_\beta P_L \nu_\alpha\right) F^{\mu\nu} F_{\mu\nu}$	$C_1^{(7)}$
	$\mathcal{O}_2^{(7)} = \frac{\alpha}{8\pi}\left(\bar{\nu}_\beta P_L \nu_\alpha\right) F^{\mu\nu} \widetilde{F}_{\mu\nu}$	$C_2^{(7)}$
	$\mathcal{O}_{5,f}^{(7)} = m_f\left(\bar{\nu}_\beta P_L \nu_\alpha\right)\left(\bar{f}f\right)$	$C_{5,f}^{(7)}$
	$\mathcal{O}_{6,f}^{(7)} = m_f\left(\bar{\nu}_\beta P_L \nu_\alpha\right)\left(\bar{f}i\gamma_5 f\right)$	$C_{6,f}^{(7)}$
	$\mathcal{O}_{7,f}^{(7)} = m_f\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\sigma_{\mu\nu} f\right)$	$C_{7,f}^{(7)}$
	$\mathcal{O}_{8,f}^{(7)} = \left(\bar{\nu}_\beta i \overleftrightarrow{\partial}_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu f\right)$	$C_{8,f}^{(7)}$
	$\mathcal{O}_{9,f}^{(7)} = \left(\bar{\nu}_\beta i \overleftrightarrow{\partial}_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu \gamma_5 f\right)$	$C_{9,f}^{(7)}$
	$\mathcal{O}_{10,f}^{(7)} = \partial_\mu\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\gamma_\nu f\right)$	$C_{10,f}^{(7)}$
	$\mathcal{O}_{11,f}^{(7)} = \partial_\mu\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\gamma_\nu \gamma_5 f\right)$	$C_{11,f}^{(7)}$

4.4 A complete generic and analytical dictionary of the collision term integrals

In last subsection, we list in table 2 the independent bases by which the invariant amplitudes $\langle \mathcal{M}^2 \rangle_{1+2\to 3+4}$ can be expressed, and conclude that the redundancy of collision term integrals from momentum-energy conservation can be removed by working with these bases directly. In this subsection, we provide the complete analytical dictionary of the collision term integrals for particle "1" and up to $k = 3$, with k the number of p_{ij}'s in the invariant amplitude. We note that a subset of this complete dictionary was presented in the appendices of Ref. [124, 126], which agrees with our results presented in this subsection as long as one specifies T_i and μ_i accordingly.

YD, J-H. Yu, arXiv: 2101.10475

NC NSIs: Neff numbers

With the complete dictionary presented in section 4, one can readily solve the Boltzmann equations for T_γ and T_{ν_α}, and thus obtain corrections to $N_{\rm eff}$. In what follows, we define these corrections as

$$\Delta N_{\rm eff} = N_{\rm eff}^{\rm SM+EFT} - N_{\rm eff}^{\rm SM}, \tag{5.1}$$

where $N_{\rm eff}^{\rm SM+EFT}$ is the theoretical prediction of $N_{\rm eff}$ with the inclusion of the NC NSI operators, and $N_{\rm eff}^{\rm SM} = 3.044$ [123, 132] that from the pure SM. For Planck, we use the current result $N_{\rm eff} = 2.99^{+0.34}_{-0.33}$ [114] at the 95% CL to obtain the constraints, and $\Delta N_{\rm eff} < 0.06$ at 95% CL for CMB-S4 [117, 143, 144, 146].

NC NSIs: Comparison

ϵ's	[103]	[97]	[82]	[83]	[84]	[85]	[90]	[98]	[35]	This work	
										Planck	CMB-S4
$\epsilon_{ee}^{e,L}$	[-0.010, 2.039]	[-1.53, 0.38]	[-0.07, 0.1]	[-0.05, 0.12]	[-0.03, 0.08]	[-0.036, 0.063]	[-0.017, 0.027] [-0.003, 0.003]	[-0.08, 0.08]	[-0.185, 0.380] [-0.130, 0.185]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon_{e\mu}^{e,L}$	[-0.179, 0.146]	[-0.84, 0.84]	-	-	[-0.13, 0.13]	-	[-0.152, 0.152] [-0.055,0.055]	[-0.33, 0.35]	[-0.025, 0.052] [-0.017, 0.040]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon_{e\tau}^{e,L}$	[-0.860, 0.350]	[-0.84, 0.84]	[-0.4, 0.4]	[-0.44, 0.44]	[-0.33, 0.33]	-	[-0.152, 0.152] [-0.055,0.055]	[-0.33, 0.35]	[-0.055, 0.023] [-0.042, 0.012]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon_{\mu\mu}^{e,L}$	[-0.364, 1.387]	-	[-0.03,0.03]	-	[-0.03, 0.03]	-	[-0.040, 0.04] [-0.010,0.010]	-	[-0.290, 0.390] [-0.192, 0.240]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon_{\mu\tau}^{e,L}$	[-0.035, 0.028]	-	[-0.1,0.1]	-	[-0.1, 0.1]	-	-	-	[-0.015, 0.013] [-0.010, 0.010]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon_{\tau\tau}^{e,L}$	[-0.350, 1.400]	-	[-0.5,0.5]	-	[-0.46, 0.24]	[-0.16 , 0.110] [0.41, 0.66]	[-0.040, 0.04] [-0.010,0.010]	-	[-0.360, 0.145] [-0.120, 0.095]	[-1.6, 1.44]	[-0.61, 0.46]
$\epsilon_{ee}^{e,R}$	[-0.010, 2.039]	[-0.07, 0.08]	[-1, 0.5]	[-0.04, 0.14]	[0.004, 0.151]	[-0.27, 0.59]	[-0.33 , 0.25] [-0.07, 0.07]	[-0.04, 0.06]	[-0.185, 0.380] [-0.130, 0.185]	[-1.6, 1.44]	[-0.39, 0.31]
$\epsilon_{e\mu}^{e,R}$	[-0.179, 0.146]	[-0.19, 0.19]	-	-	[-0.13, 0.13]	-	[-0.236, 0.236] [-0.08, 0.08]	[-0.15, 0.16]	[-0.025, 0.052] [-0.017, 0.040]	[-1.6, 1.44]	[-0.39, 0.31]
$\epsilon_{e\tau}^{e,R}$	[-0.860, 0.350]	[-0.19, 0.19]	[-0.7, 0.7]	[-0.27, 0.27]	[-0.05 , 0.05] [-0.28, 0.28]	-	[-0.236, 0.236] [-0.08, 0.08]	[-0.15, 0.16]	[-0.055, 0.023] [-0.042, 0.012]	[-1.6, 1.44]	[-0.39, 0.31]
$\epsilon_{\mu\mu}^{e,R}$	[-0.364, 1.387]	-	[-0.03,0.03]	-	[-0.03, 0.03]	-	[-0.10 , 0.12] [-0.006, 0.006]	-	[-0.290, 0.390] [-0.192, 0.240]	[-1.6, 1.44]	[-0.39, 0.31]
$\epsilon_{\mu\tau}^{e,R}$	[-0.035, 0.028]	-	[-0.1,0.1]	-	[-0.1, 0.1]	-	-	-	[-0.015, 0.013] [-0.010, 0.010]	[-1.6, 1.44]	[-0.39, 0.31]
$\epsilon_{\tau\tau}^{e,R}$	[-0.350, 1.400]	-	[-0.5,0.5]	-	[-0.25, 0.43]	[-1.05, 0.31]	[-0.10 , 0.12] [-0.006, 0.006]	-	[-0.360, 0.145] [-0.120, 0.095]	[-1.6, 1.44]	[-0.39, 0.31]

Table 4. Summary of constraints on dimension-6 neutrino-electron NC NSIs from previous studies and this work. Constraints from a global fitting of all kinds of neutrino oscillation data plus the COHERENT result are obtained in Ref. [103], the TEXONO collaboration in Ref. [97], the LEP, LSND and CHARM-II experiments in Ref. [82], a global analysis of $\nu_e e$ and $\bar{\nu}_e e$ scattering data from LSND, Irvine, Rovno and MUNU experiments in Ref. [83], OPAL, ALEPH, L3, DELPHI, LSND, CHARM-II, Irvine, Rovno and MUNU experiments in Ref. [84], solar and reactor neutrino experiments in Ref. [85], low-energy solar neutrinos at source and detector from the Borexino experiment in Ref. [90], a global analysis of short baseline νe and $\bar{\nu} e$ data from LSND, LAMPF, Irvine, Rovno, MUNU, TEXONO and KRANOYARSK in Ref. [98], and DUNE in Ref. [35].