Exploring the ultraviolet from neutrino oscillations and Neff in the EFT framework

Yong Du

email: yongdu@itp.ac.cn

HEFT-2021, April 15 2021

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

YD, J-H. Yu, arXiv: 2101.10475 (To appear in JHEP)

Overview

SMEFT@LHC: Top sector, Higgs sector, PDF etc (talks yesterday and today)

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E

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PVES (MOLLER, P2)

Neutrino oscillation

Precision cosmology

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← *My focus today*

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- **Charge-Current (CC) NSIs: from terrestrial neutrino oscillation experiments (dim-6 SMEFT operators only)**

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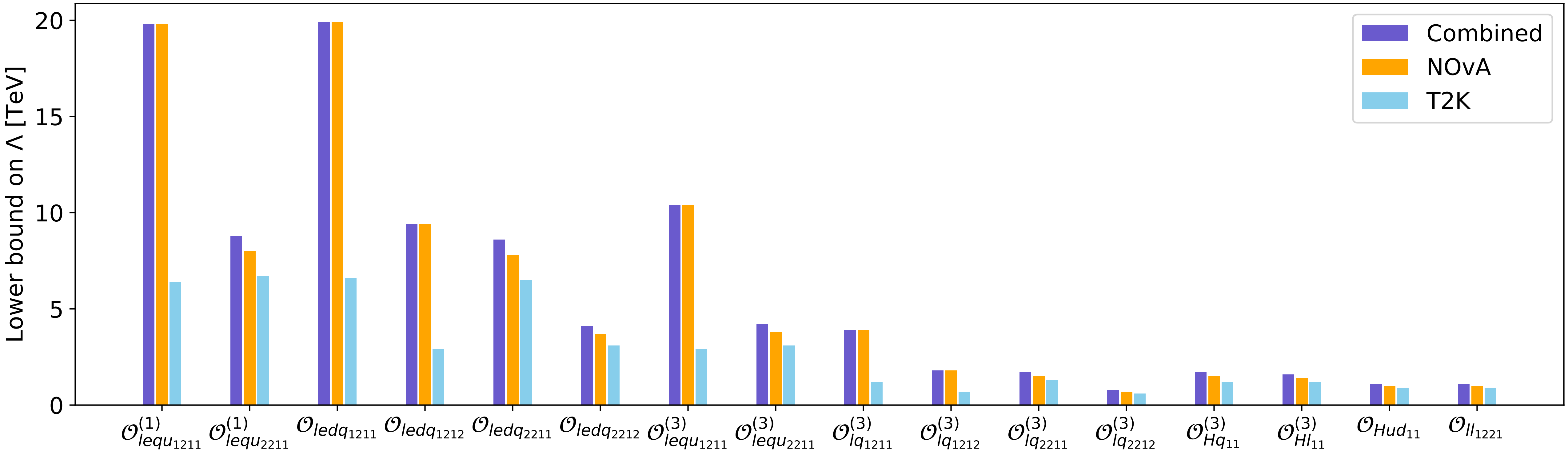
  YD, H-L. Li, J. Tang, S. Vihonen, J-H. Yu, JHEP 03(2021) 019

- **Neutral-Current (NC) NSIs: Neff from Planck and CMB-S4 (ν-ν, ν-e, ν-γ operators up to dim-7)**

  YD, J-H. Yu, arXiv: 2101.10475 (To appear in JHEP)

Spoiler: CC NSIs



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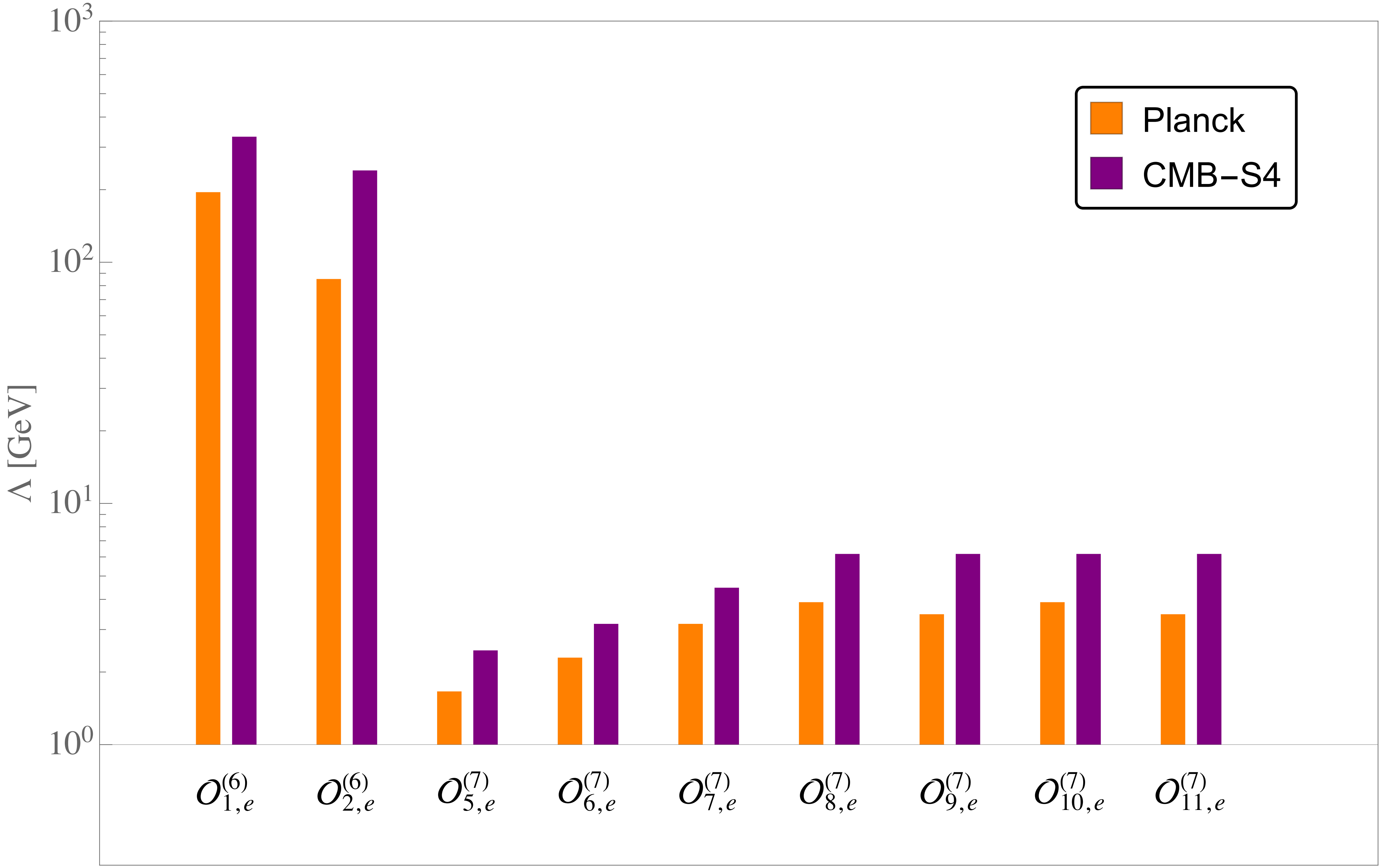

CC NSIs

What neutrino experimentalists measure: Mismatch between 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
$\lvert\epsilon^s_{\mu e}\rvert$	0.004	
$\lvert\epsilon^s_{\mu\mu}\rvert$	0.021	T2K [21, 72, 73], NOνA [24]
$\lvert\epsilon^s_{\mu\tau}\rvert$	0.080	
$\lvert\epsilon^d_{ee}\rvert$	0.007	
$\lvert\epsilon^d_{\mu e}\rvert$	0.018	
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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

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

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

CC NSIs

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$$\mathcal{L} \supset -\frac{2V_{ud}}{v^2}\{\, [1+\epsilon_L]_{\alpha\beta} (\bar{u}\gamma^\mu P_L d)(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta) + [\epsilon_R]_{\alpha\beta} (\bar{u}\gamma^\mu P_R d)(\bar{\ell}_\alpha \gamma_\mu P_L \nu_\beta)$$
$$+\frac{1}{2}[\epsilon_S]_{\alpha\beta}(\bar{u}d)(\bar{\ell}_\alpha P_L \nu_\beta) - \frac{1}{2}[\epsilon_P]_{\alpha\beta}(\bar{u}\gamma_5 d)(\bar{\ell}_\alpha P_L \nu_\beta) + \frac{1}{4}[\epsilon_T]_{\alpha\beta}(\bar{u}\sigma^{\mu\nu} P_L d)(\bar{\ell}_\alpha \sigma_{\mu\nu} P_L \nu_\beta) + \text{ h.c.}$$

Connection between the two:

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

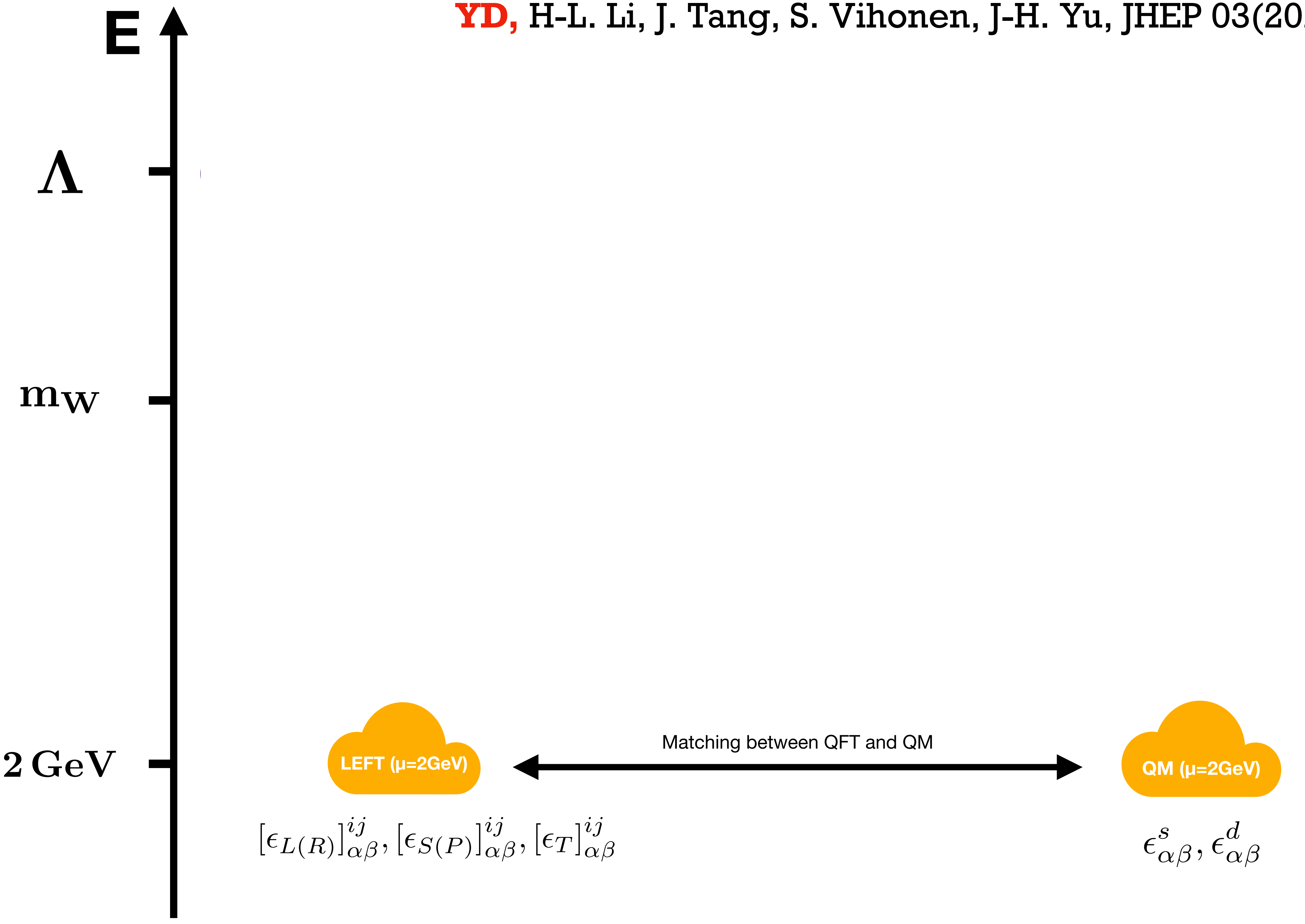
$$\epsilon^d_{\beta e} = \left[\epsilon_L + \frac{1-3g_A^2}{1+3g_A^2}\epsilon_R - \frac{m_e}{E_\nu - \Delta}\left(\frac{g_S}{1+3g_A^2}\epsilon_S - \frac{3g_A g_T}{1+3g_A^2}\epsilon_T\right)\right]_{e\beta},$$

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

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

CC NSIs

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



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

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

CC NSIs

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E

Λ

m_W

$2\,\mathrm{GeV}$

See Jiang-Hao Yu's and Chris Murphy's talks for example

Q: How to generate these NSIs?

LEFT (μ=2GeV) ⟷ Matching between QFT and QM ⟷ QM (μ=2GeV)

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

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CC NSIs

Xiaochuan Lu's and Joydeep Chakrabortty's talks

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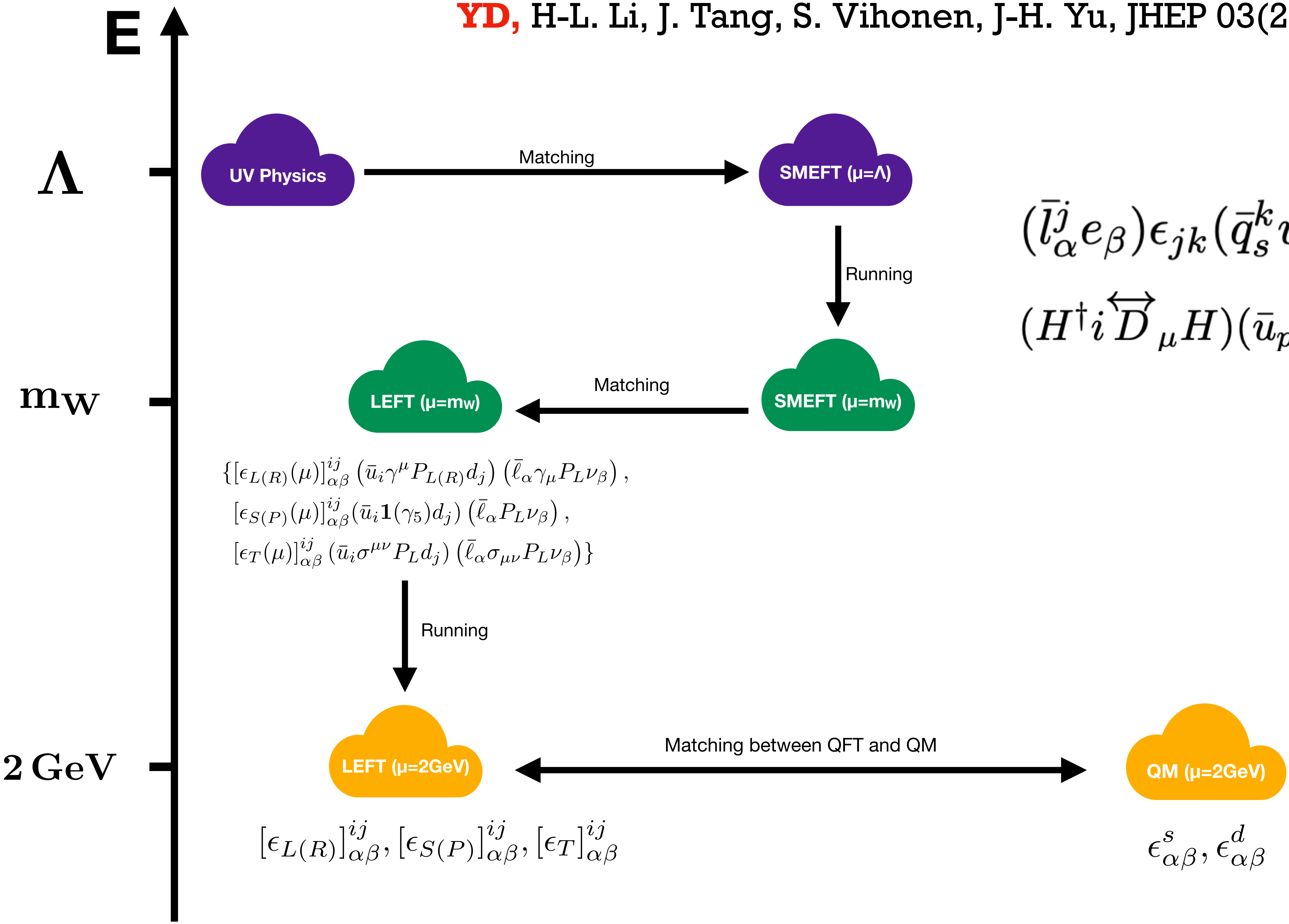


$$(\bar{l}^j_\alpha e_\beta)\epsilon_{jk}(\bar{q}^k_s u_t)$$

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

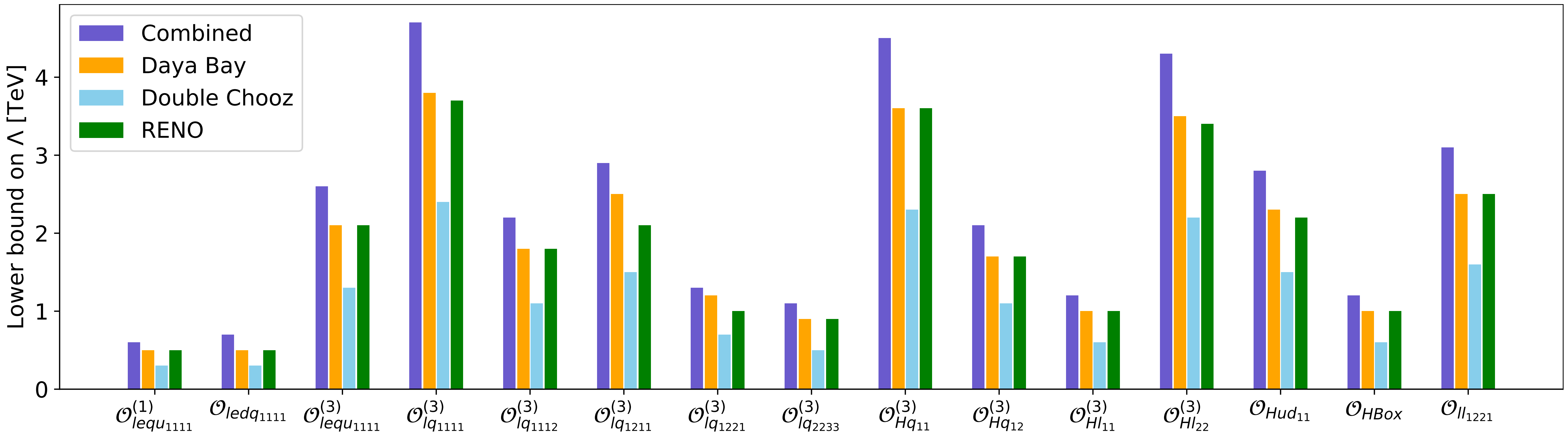
$$\{[\epsilon_{L(R)}(\mu)]^{ij}_{\alpha\beta}\,(\bar{u}_i\gamma^\mu P_{L(R)}d_j)\,(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)\,,$$
$$[\epsilon_{S(P)}(\mu)]^{ij}_{\alpha\beta}(\bar{u}_i\mathbf{1}(\gamma_5)d_j)\,(\bar{\ell}_\alpha P_L\nu_\beta)\,,$$
$$[\epsilon_T(\mu)]^{ij}_{\alpha\beta}\,(\bar{u}_i\sigma^{\mu\nu}P_L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

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

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

Results: CC NSIs

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



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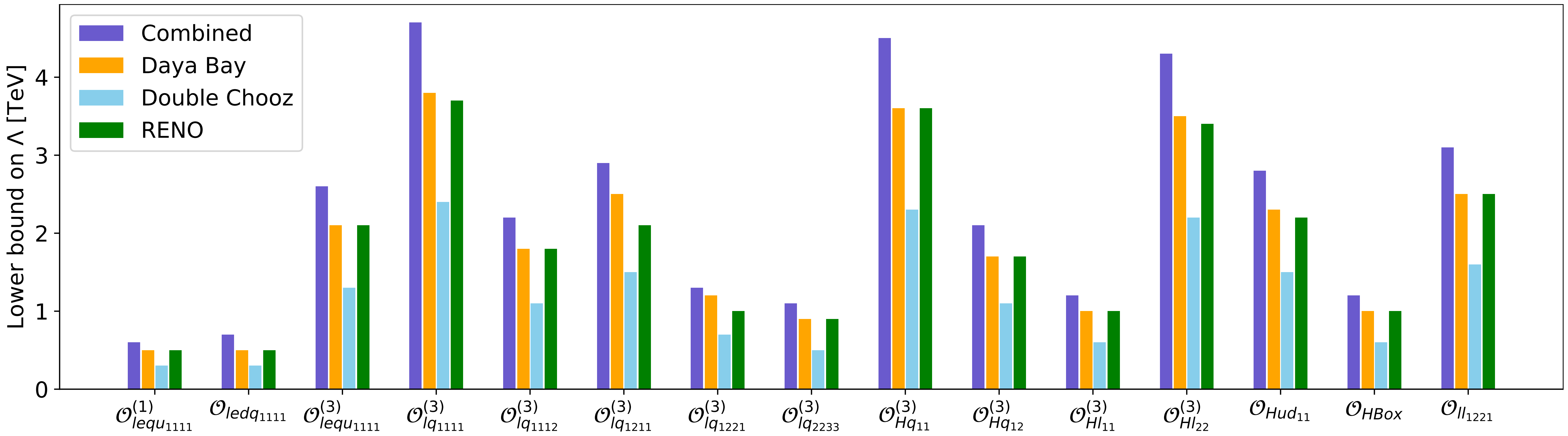

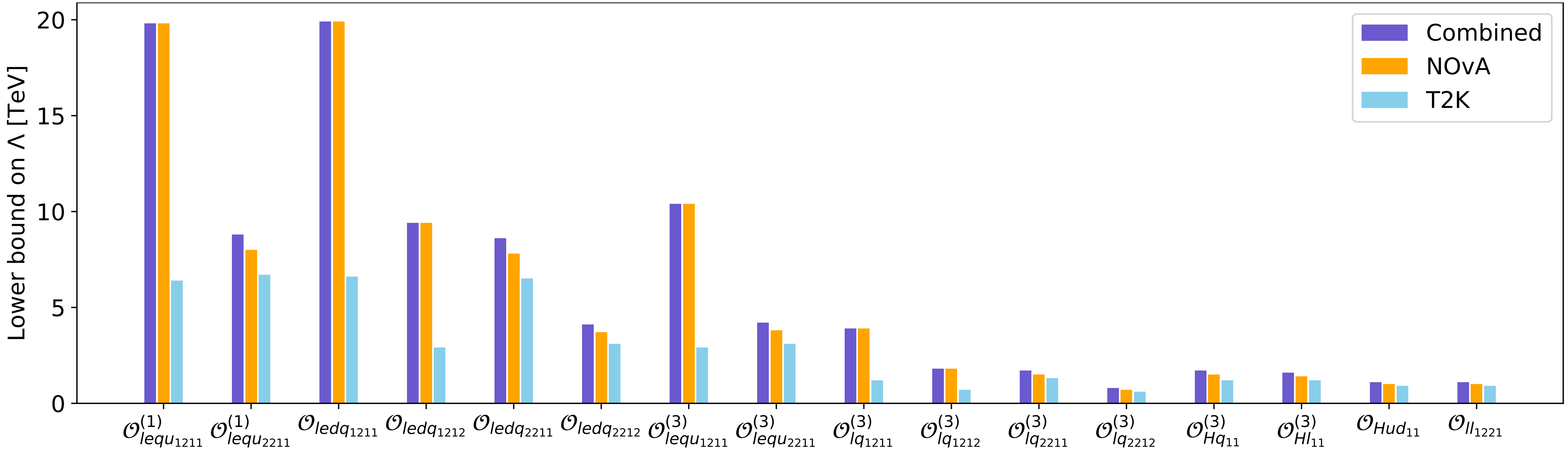

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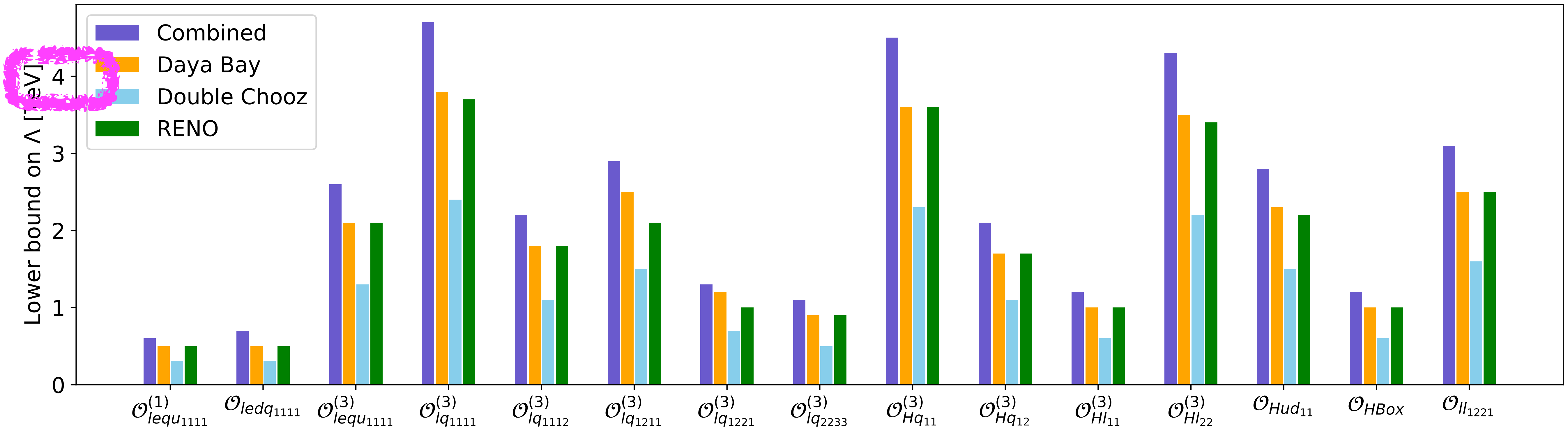

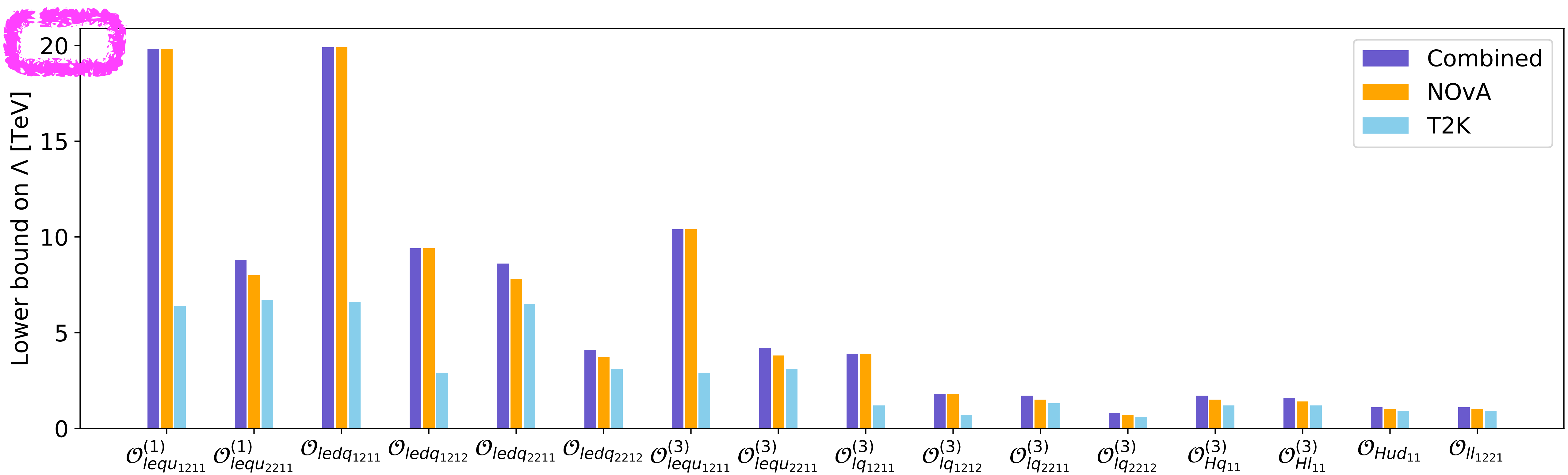

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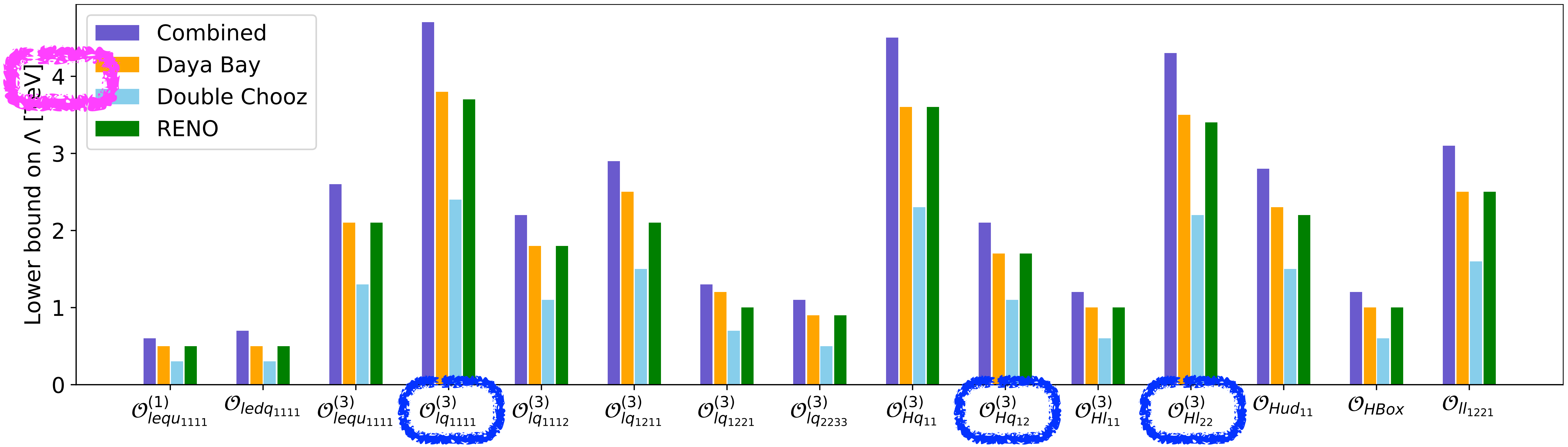

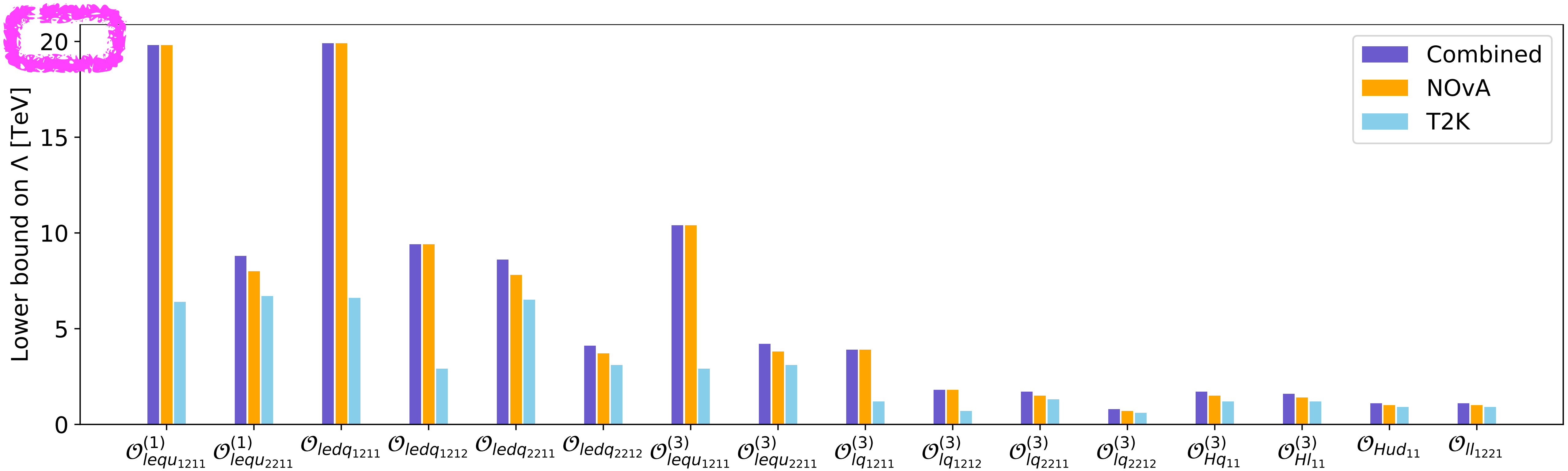

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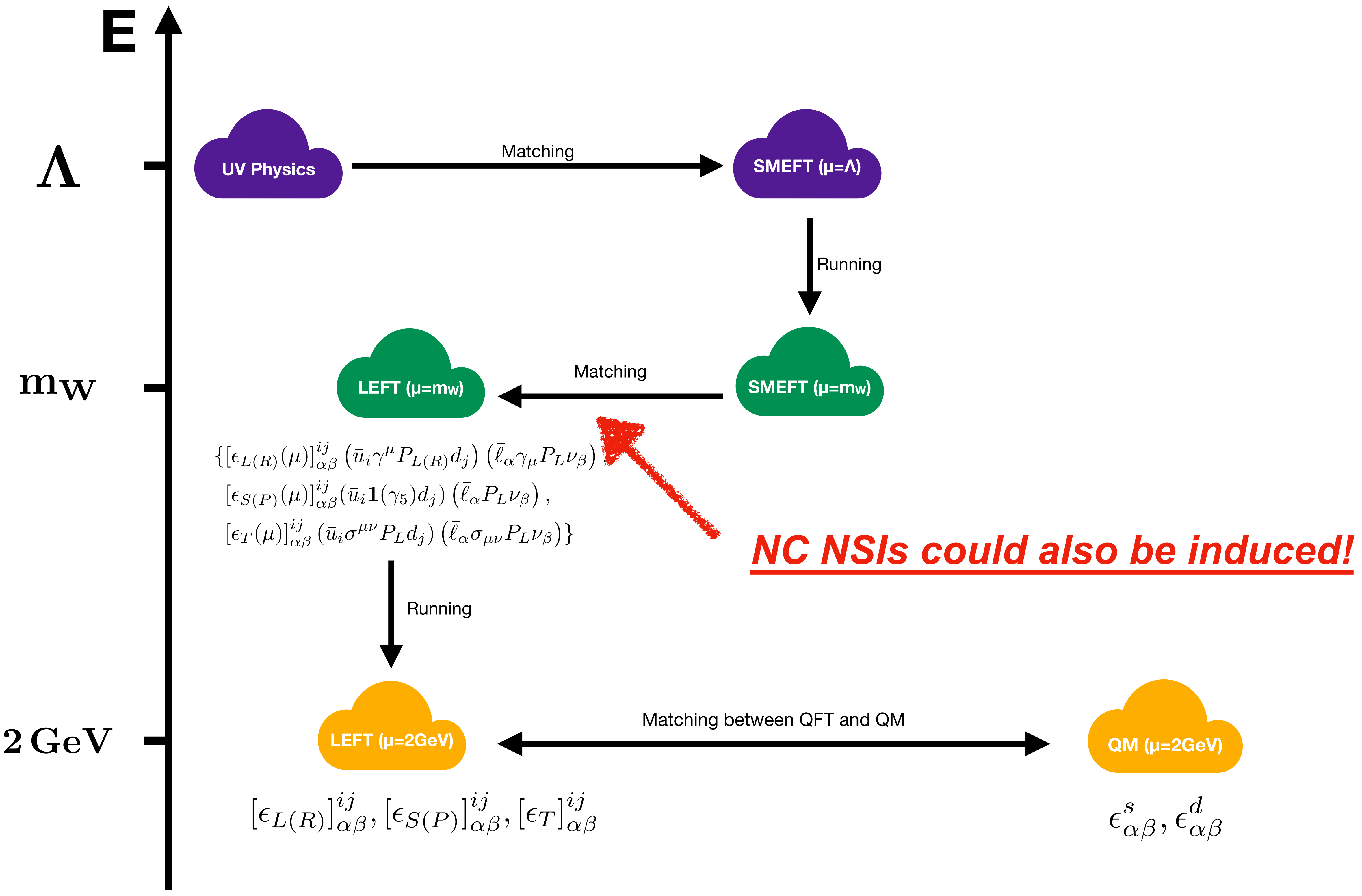
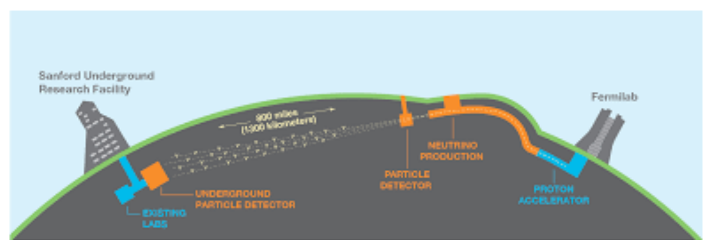
NC NSIs

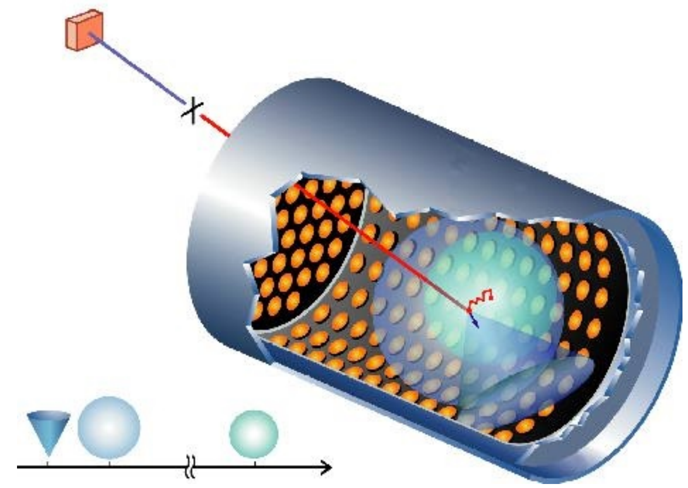

E
Λ
m_W
2 GeV
UV Physics
Matching
SMEFT (μ=Λ)
Running
LEFT (μ=mw)
Matching
SMEFT (μ=mw)
$\{[\epsilon_{L(R)}(\mu)]^{ij}_{\alpha\beta}\,(\bar{u}_i\gamma^\mu P_{L(R)}d_j)\,(\bar{\ell}_\alpha\gamma_\mu P_L\nu_\beta)\,,$
$[\epsilon_{S(P)}(\mu)]^{ij}_{\alpha\beta}(\bar{u}_i\mathbf{1}(\gamma_5)d_j)\,(\bar{\ell}_\alpha P_L\nu_\beta)\,,$
$[\epsilon_T(\mu)]^{ij}_{\alpha\beta}\,(\bar{u}_i\sigma^{\mu\nu}P_L d_j)\,(\bar{\ell}_\alpha\sigma_{\mu\nu}P_L\nu_\beta)\}$
NC NSIs could also be induced!
Running
LEFT (μ=2GeV)
Matching between QFT and QM
QM (μ=2GeV)
$[\epsilon_{L(R)}]^{ij}_{\alpha\beta},\,[\epsilon_{S(P)}]^{ij}_{\alpha\beta},\,[\epsilon_T]^{ij}_{\alpha\beta}$
$\epsilon^s_{\alpha\beta},\,\epsilon^d_{\alpha\beta}$

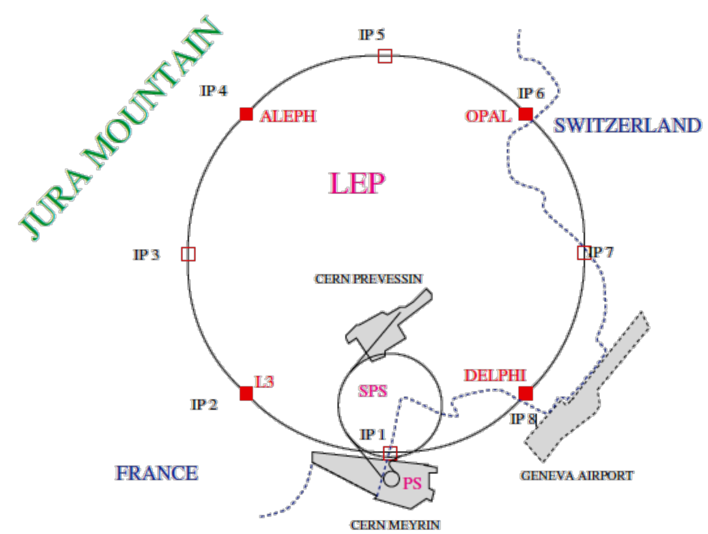
NC NSIs

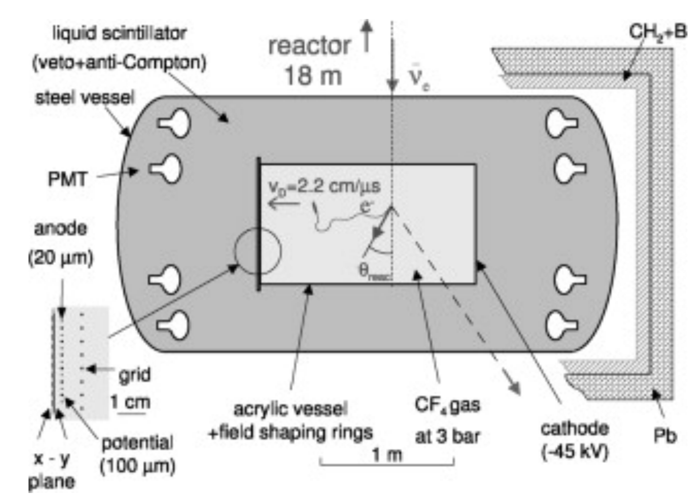
$$\mathcal{L}_{\rm NSI}^{\rm NC} = -2\sqrt{2}G_F \sum_{\alpha,\beta,f,P} \epsilon_{\alpha\beta}^{f,P} \left(\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta\right)\left(\bar{f}\gamma^\mu P f\right)$$

Internal – Wiki









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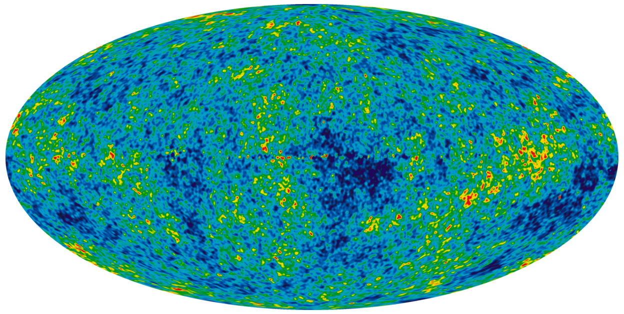

$$\rho_R = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right]\rho_\gamma$$

NC NSIs

Q: How NC NSIs affect neutrino decoupling?

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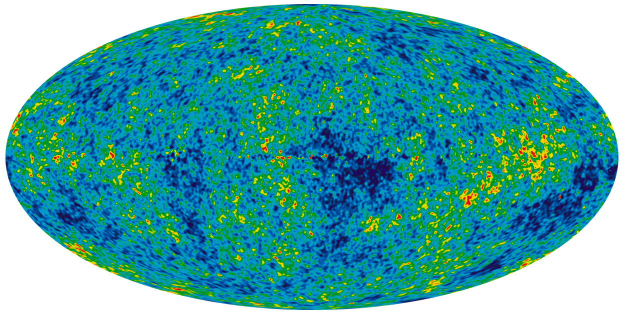

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NC NSIs

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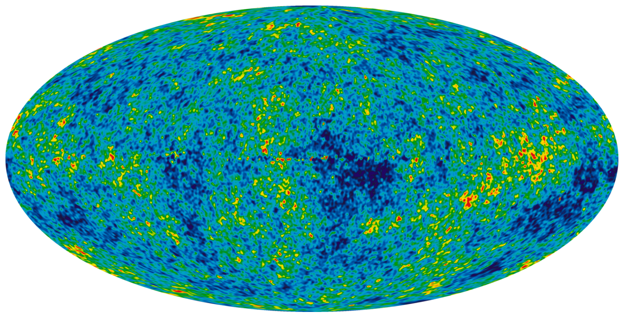
YD, J-H. Yu, arXiv: 2101.10475

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	$\mathcal{O}_1^{(7)} = \frac{\alpha}{12\pi}\left(\bar{\nu}_\beta P_L \nu_\alpha\right) F^{\mu\nu} F_{\mu\nu}$	$C_1^{(7)}$
	$\mathcal{O}_2^{(7)} = \frac{\alpha}{8\pi}\left(\bar{\nu}_\beta P_L \nu_\alpha\right) F^{\mu\nu} \widetilde{F}_{\mu\nu}$	$C_2^{(7)}$
	$\mathcal{O}_{5,f}^{(7)} = m_f\left(\bar{\nu}_\beta P_L \nu_\alpha\right)\left(\bar{f} f\right)$	$C_{5,f}^{(7)}$
	$\mathcal{O}_{6,f}^{(7)} = m_f\left(\bar{\nu}_\beta P_L \nu_\alpha\right)\left(\bar{f} i\gamma_5 f\right)$	$C_{6,f}^{(7)}$
	$\mathcal{O}_{7,f}^{(7)} = m_f\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\sigma_{\mu\nu} f\right)$	$C_{7,f}^{(7)}$
	$\mathcal{O}_{8,f}^{(7)} = \left(\bar{\nu}_\beta i \overleftrightarrow{\partial}_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu f\right)$	$C_{8,f}^{(7)}$
	$\mathcal{O}_{9,f}^{(7)} = \left(\bar{\nu}_\beta i \overleftrightarrow{\partial}_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu \gamma_5 f\right)$	$C_{9,f}^{(7)}$
	$\mathcal{O}_{10,f}^{(7)} = \partial_\mu\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\gamma_\nu f\right)$	$C_{10,f}^{(7)}$
	$\mathcal{O}_{11,f}^{(7)} = \partial_\mu\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\gamma_\nu \gamma_5 f\right)$	$C_{11,f}^{(7)}$



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

NC NSIs

Q: How NC NSIs affect neutrino decoupling?

YD, J-H. Yu, arXiv: 2101.10475

Majoron model

U(1)’ model

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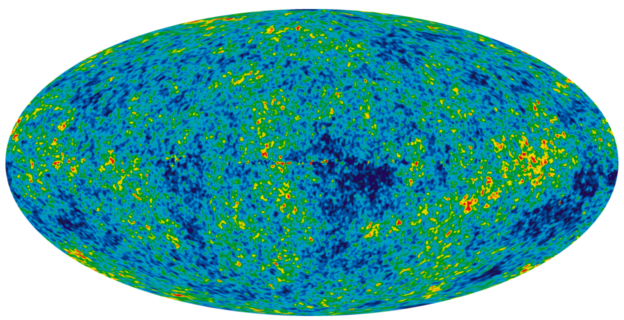
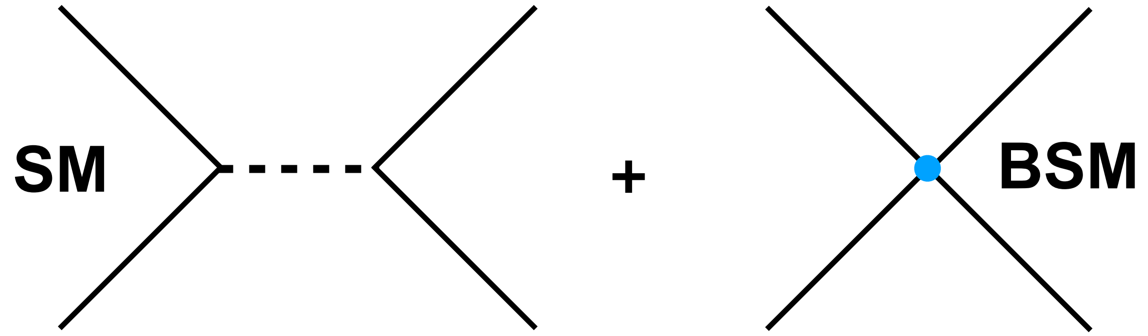
	$\mathcal{O}_{7,f}^{(7)} = m_f\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\sigma_{\mu\nu} f\right)$	$C_{7,f}^{(7)}$
	$\mathcal{O}_{8,f}^{(7)} = \left(\bar{\nu}_\beta i \overleftrightarrow{\partial}_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu f\right)$	$C_{8,f}^{(7)}$
	$\mathcal{O}_{9,f}^{(7)} = \left(\bar{\nu}_\beta i \overleftrightarrow{\partial}_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu \gamma_5 f\right)$	$C_{9,f}^{(7)}$
	$\mathcal{O}_{10,f}^{(7)} = \partial_\mu\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\gamma_\nu f\right)$	$C_{10,f}^{(7)}$
	$\mathcal{O}_{11,f}^{(7)} = \partial_\mu\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\gamma_\nu \gamma_5 f\right)$	$C_{11,f}^{(7)}$



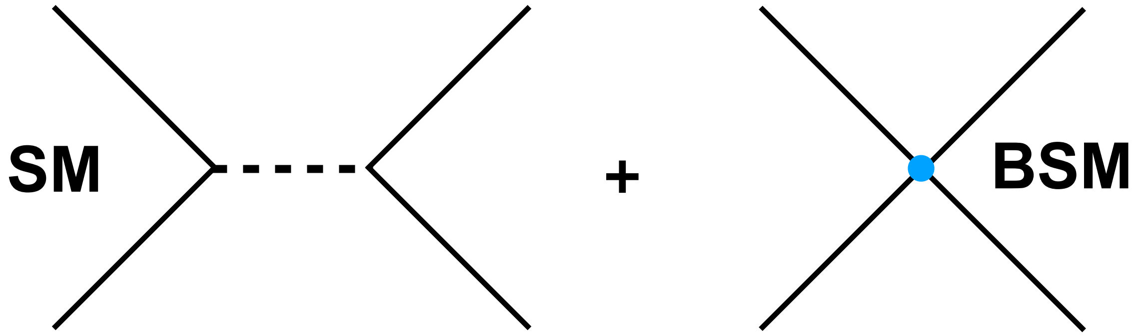
$$\rho_R = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right]\rho_\gamma$$

NC NSIs



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	$\mathcal{O}_1^{(7)} = \frac{\alpha}{12\pi}\left(\bar{\nu}_\beta P_L \nu_\alpha\right) F^{\mu\nu} F_{\mu\nu}$	$C_1^{(7)}$
	$\mathcal{O}_2^{(7)} = \frac{\alpha}{8\pi}\left(\bar{\nu}_\beta P_L \nu_\alpha\right) F^{\mu\nu} \widetilde{F}_{\mu\nu}$	$C_2^{(7)}$
	$\mathcal{O}_{5,f}^{(7)} = m_f\left(\bar{\nu}_\beta P_L \nu_\alpha\right)\left(\bar{f} f\right)$	$C_{5,f}^{(7)}$
	$\mathcal{O}_{6,f}^{(7)} = m_f\left(\bar{\nu}_\beta P_L \nu_\alpha\right)\left(\bar{f} i\gamma_5 f\right)$	$C_{6,f}^{(7)}$
	$\mathcal{O}_{7,f}^{(7)} = m_f\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\sigma_{\mu\nu} f\right)$	$C_{7,f}^{(7)}$
	$\mathcal{O}_{8,f}^{(7)} = \left(\bar{\nu}_\beta i \overleftrightarrow{\partial}_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu f\right)$	$C_{8,f}^{(7)}$
	$\mathcal{O}_{9,f}^{(7)} = \left(\bar{\nu}_\beta i \overleftrightarrow{\partial}_\mu P_L \nu_\alpha\right)\left(\bar{f}\gamma^\mu \gamma_5 f\right)$	$C_{9,f}^{(7)}$
	$\mathcal{O}_{10,f}^{(7)} = \partial_\mu\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\gamma_\nu f\right)$	$C_{10,f}^{(7)}$
	$\mathcal{O}_{11,f}^{(7)} = \partial_\mu\left(\bar{\nu}_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar{f}\gamma_\nu \gamma_5 f\right)$	$C_{11,f}^{(7)}$

NC NSIs

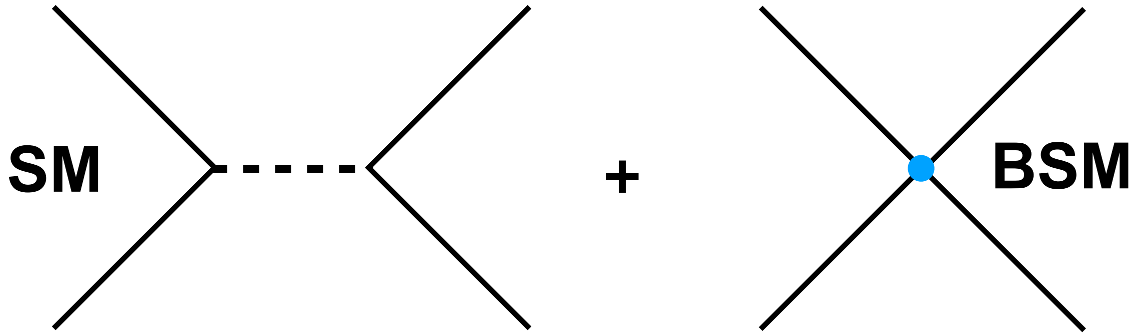


$$\frac{dn}{dt} + 3Hn = \int g \frac{d^3p}{(2\pi)^3} \mathcal{C}[f],$$

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

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	$\mathcal{O}_1^{(7)} = \frac{\alpha}{12\pi}\left(\bar\nu_\beta P_L \nu_\alpha\right) F^{\mu\nu} F_{\mu\nu}$	$C_1^{(7)}$
	$\mathcal{O}_2^{(7)} = \frac{\alpha}{8\pi}\left(\bar\nu_\beta P_L \nu_\alpha\right) F^{\mu\nu} \widetilde{F}_{\mu\nu}$	$C_2^{(7)}$
	$\mathcal{O}_{5,f}^{(7)} = m_f \left(\bar\nu_\beta P_L \nu_\alpha\right)\left(\bar f f\right)$	$C_{5,f}^{(7)}$
	$\mathcal{O}_{6,f}^{(7)} = m_f \left(\bar\nu_\beta P_L \nu_\alpha\right)\left(\bar f i\gamma_5 f\right)$	$C_{6,f}^{(7)}$
	$\mathcal{O}_{7,f}^{(7)} = m_f \left(\bar\nu_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar f \sigma_{\mu\nu} f\right)$	$C_{7,f}^{(7)}$
	$\mathcal{O}_{8,f}^{(7)} = \left(\bar\nu_\beta i \overleftrightarrow{\partial}_\mu P_L \nu_\alpha\right)\left(\bar f \gamma^\mu f\right)$	$C_{8,f}^{(7)}$
	$\mathcal{O}_{9,f}^{(7)} = \left(\bar\nu_\beta i \overleftrightarrow{\partial}_\mu P_L \nu_\alpha\right)\left(\bar f \gamma^\mu \gamma_5 f\right)$	$C_{9,f}^{(7)}$
	$\mathcal{O}_{10,f}^{(7)} = \partial_\mu \left(\bar\nu_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar f \gamma_\nu f\right)$	$C_{10,f}^{(7)}$
	$\mathcal{O}_{11,f}^{(7)} = \partial_\mu \left(\bar\nu_\beta \sigma^{\mu\nu} P_L \nu_\alpha\right)\left(\bar f \gamma_\nu \gamma_5 f\right)$	$C_{11,f}^{(7)}$

NC NSIs



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

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

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

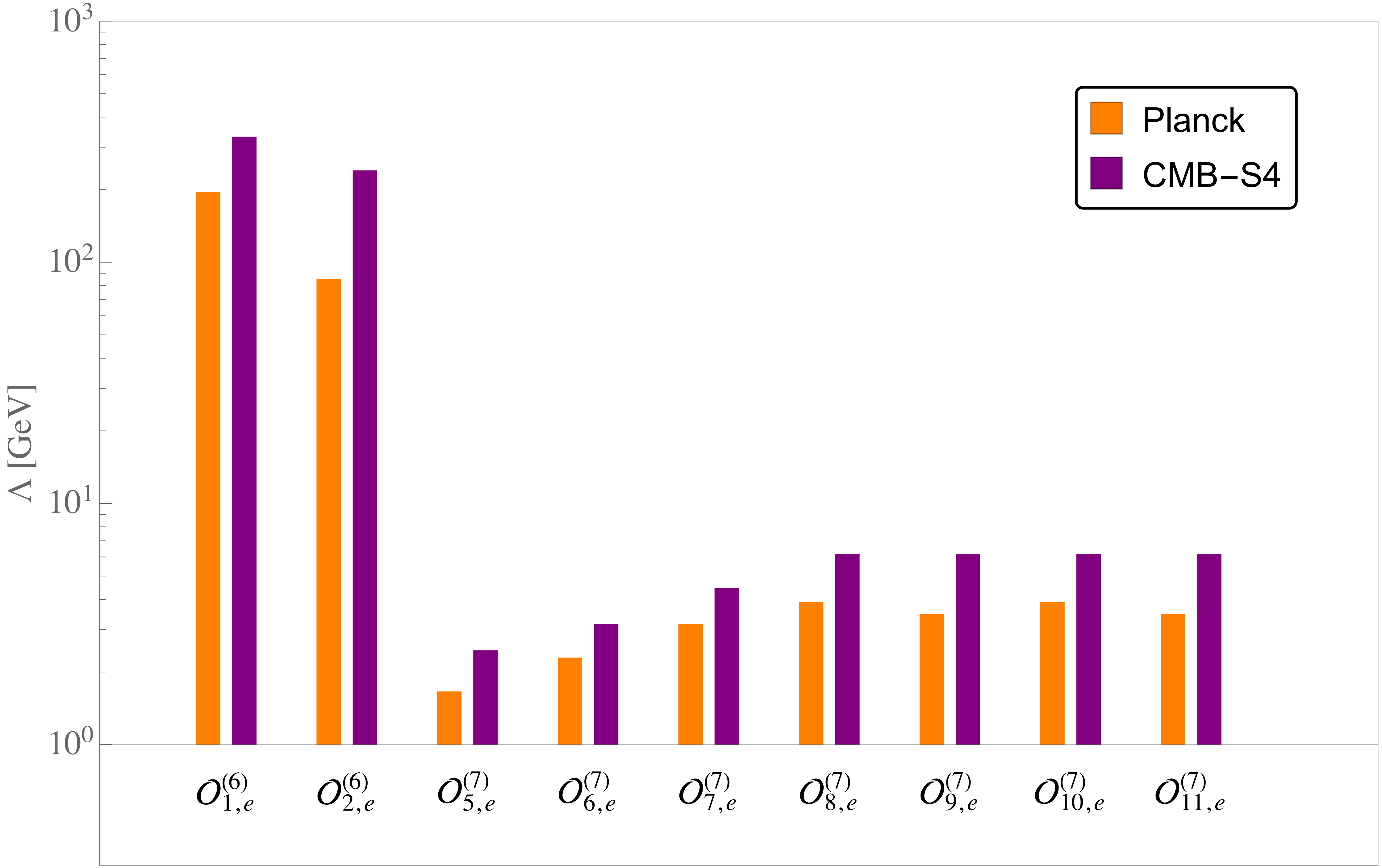
4.4 A complete generic and analytical dictionary of the collision term integrals

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

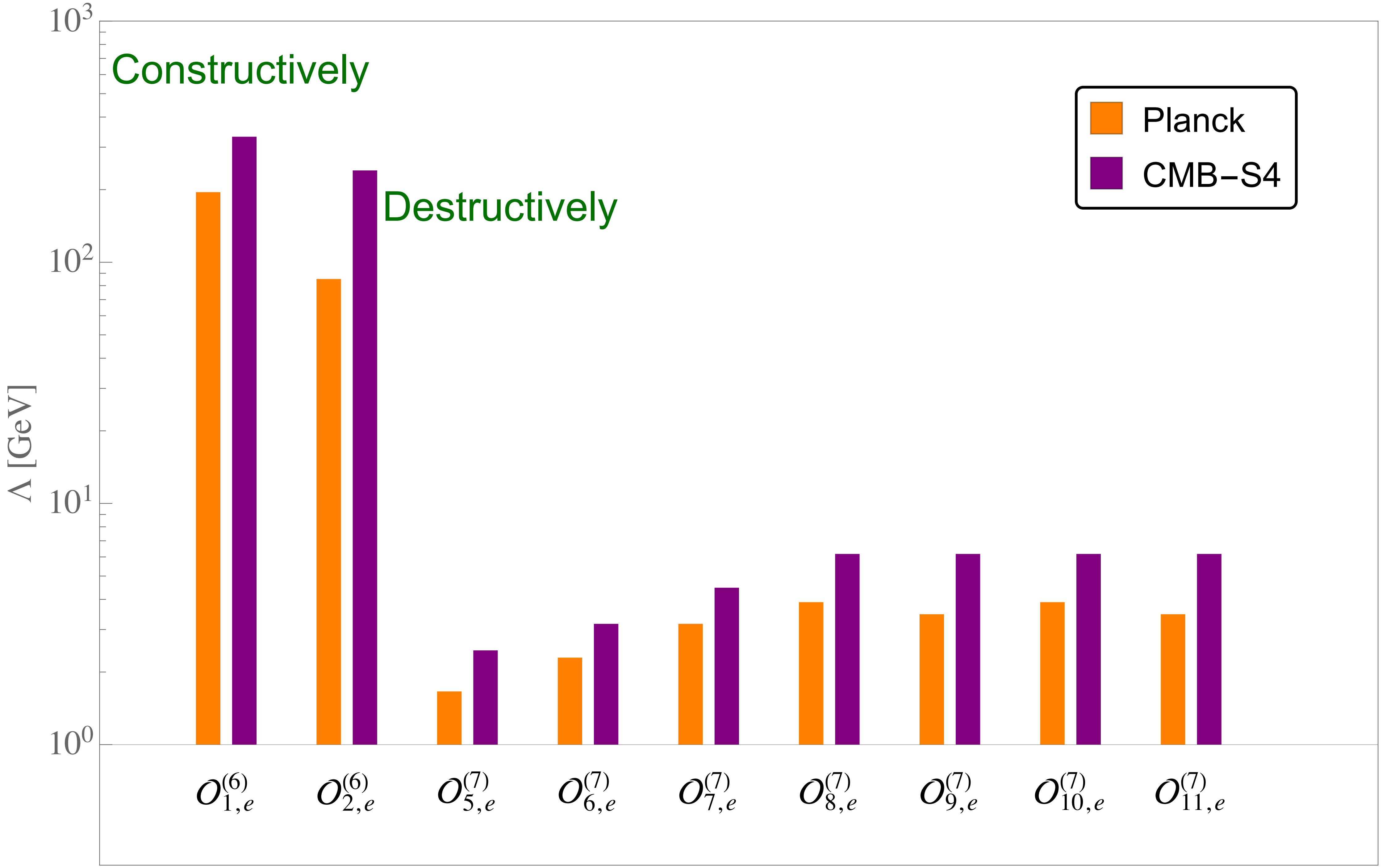
Results: NC NSIs

YD, J-H. Yu, arXiv: 2101.10475



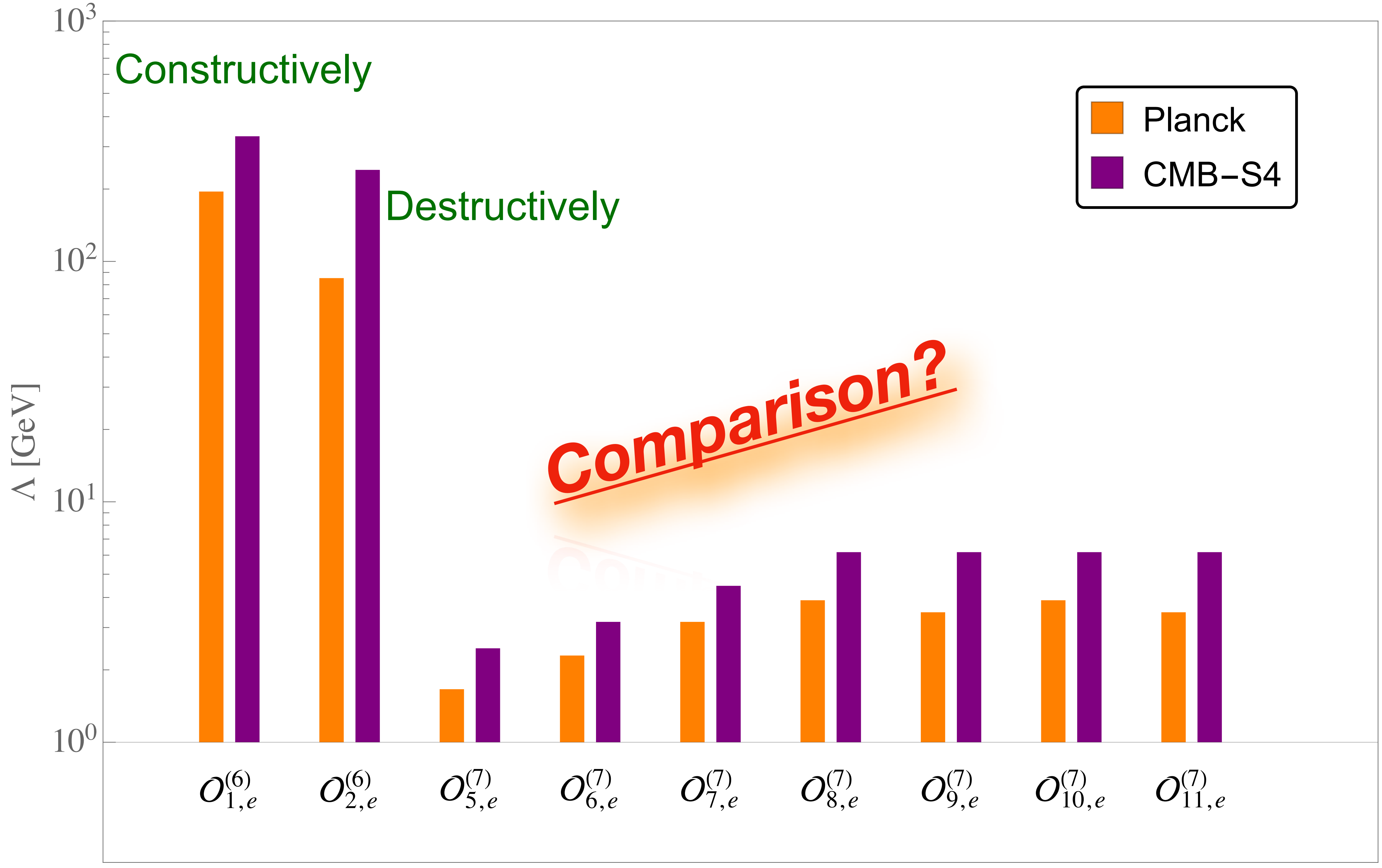
Results: NC NSIs

YD, J-H. Yu, arXiv: 2101.10475



Results: NC NSIs

YD, J-H. Yu, arXiv: 2101.10475



Results: NC NSIs comparison

YD, J-H. Yu, arXiv: 2101.10475

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

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]
$\epsilon_{ee}^{e,L}$	[-0.010, 2.039]
$\epsilon_{e\mu}^{e,L}$	[-0.179, 0.146]
$\epsilon_{e\tau}^{e,L}$	[-0.860, 0.350]
$\epsilon_{\mu\mu}^{e,L}$	[-0.364, 1.387]
$\epsilon_{\mu\tau}^{e,L}$	[-0.035, 0.028]
$\epsilon_{\tau\tau}^{e,L}$	[-0.350, 1.400]
$\epsilon_{ee}^{e,R}$	[-0.010, 2.039]
$\epsilon_{e\mu}^{e,R}$	[-0.179, 0.146]
$\epsilon_{e\tau}^{e,R}$	[-0.860, 0.350]
$\epsilon_{\mu\mu}^{e,R}$	[-0.364, 1.387]
$\epsilon_{\mu\tau}^{e,R}$	[-0.035, 0.028]
$\epsilon_{\tau\tau}^{e,R}$	[-0.350, 1.400]

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]
$\epsilon_{ee}^{e,L}$	[-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]
$\epsilon_{e\mu}^{e,L}$	[-0.179, 0.146]	[-0.84, 0.84]	-	-	[-0.13, 0.13]	-	[-0.152, 0.152] [-0.055,0.055]	[-0.33, 0.35]
$\epsilon_{e\tau}^{e,L}$	[-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]
$\epsilon_{\mu\mu}^{e,L}$	[-0.364, 1.387]	-	[-0.03,0.03]	-	[-0.03, 0.03]	-	[-0.040, 0.04] [-0.010,0.010]	-
$\epsilon_{\mu\tau}^{e,L}$	[-0.035, 0.028]	-	[-0.1,0.1]	-	[-0.1, 0.1]	-	-	-
$\epsilon_{\tau\tau}^{e,L}$	[-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]	-
$\epsilon_{ee}^{e,R}$	[-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]
$\epsilon_{e\mu}^{e,R}$	[-0.179, 0.146]	[-0.19, 0.19]	-	-	[-0.13, 0.13]	-	[-0.236, 0.236] [-0.08, 0.08]	[-0.15, 0.16]
$\epsilon_{e\tau}^{e,R}$	[-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]
$\epsilon_{\mu\mu}^{e,R}$	[-0.364, 1.387]	-	[-0.03,0.03]	-	[-0.03, 0.03]	-	[-0.10 , 0.12] [-0.006, 0.006]	-
$\epsilon_{\mu\tau}^{e,R}$	[-0.035, 0.028]	-	[-0.1,0.1]	-	[-0.1, 0.1]	-	-	-
$\epsilon_{\tau\tau}^{e,R}$	[-0.350, 1.400]	-	[-0.5,0.5]	-	[-0.25, 0.43]	[-1.05, 0.31]	[-0.10 , 0.12] [-0.006, 0.006]	-

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]
$\epsilon_{ee}^{e,L}$	[-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]
$\epsilon_{e\mu}^{e,L}$	[-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]
$\epsilon_{e\tau}^{e,L}$	[-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]
$\epsilon_{\mu\mu}^{e,L}$	[-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]
$\epsilon_{\mu\tau}^{e,L}$	[-0.035, 0.028]	-	[-0.1,0.1]	-	[-0.1, 0.1]	-	-	-	[-0.015, 0.013] [-0.010, 0.010]
$\epsilon_{\tau\tau}^{e,L}$	[-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]
$\epsilon_{ee}^{e,R}$	[-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]
$\epsilon_{e\mu}^{e,R}$	[-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]
$\epsilon_{e\tau}^{e,R}$	[-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]
$\epsilon_{\mu\mu}^{e,R}$	[-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]
$\epsilon_{\mu\tau}^{e,R}$	[-0.035, 0.028]	-	[-0.1,0.1]	-	[-0.1, 0.1]	-	-	-	[-0.015, 0.013] [-0.010, 0.010]
$\epsilon_{\tau\tau}^{e,R}$	[-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]

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]
$\epsilon_{\mu\tau}^{e,R}$	[-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]
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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	
										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]
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$\epsilon_{\tau\tau}^{e,L}$	[-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]
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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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$\epsilon_{e\mu}^{e,L}$	[-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]	-	[-0.04 , 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]

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.

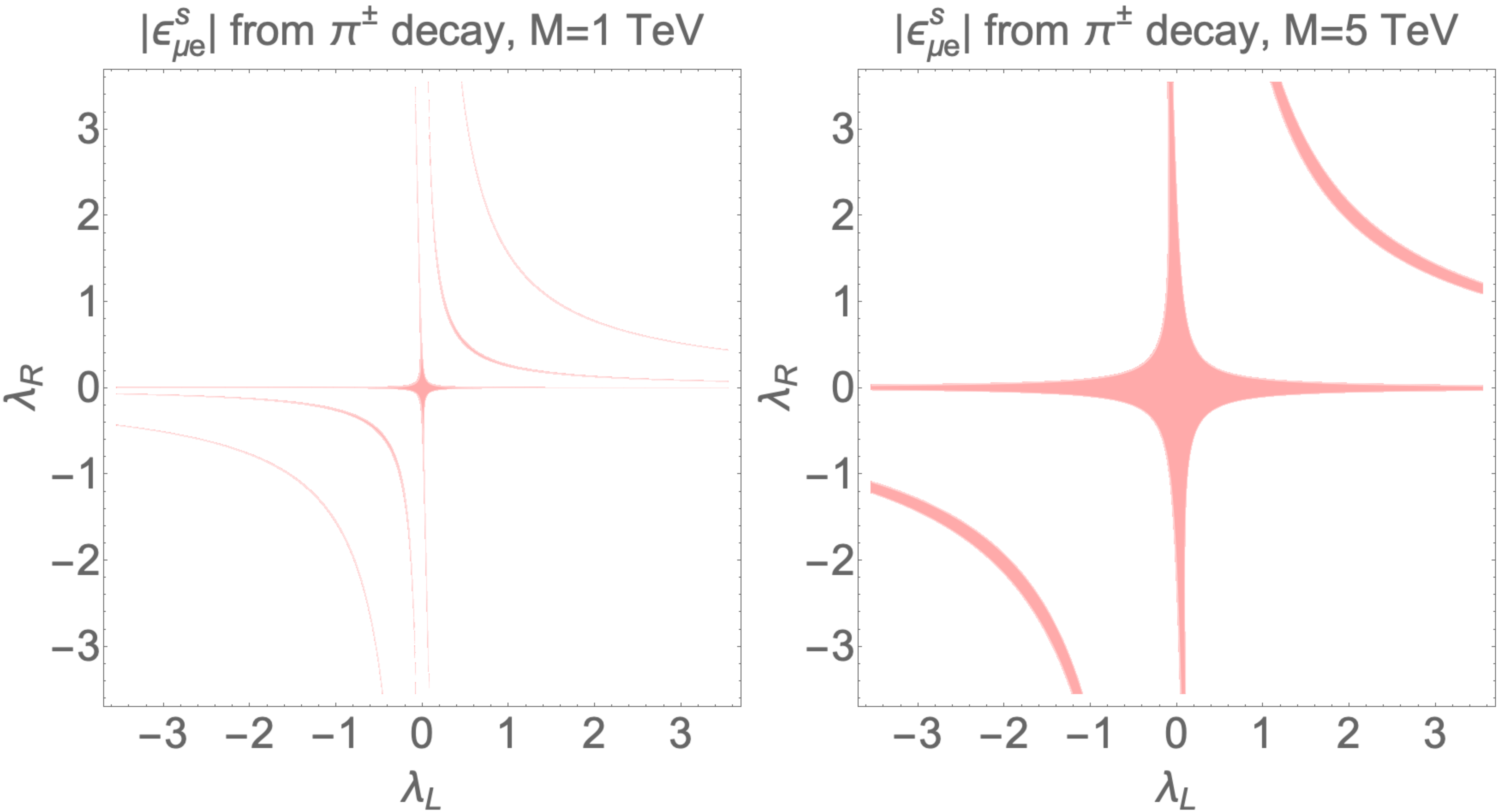
- For NC NSIs up to dim-7, constraints from precision measurements of Neff (Planck, CMB-S4) are complementary to other type of neutrino experiments (COHERENT, collider, solar and reactor neutrino experiments, DUNE etc).

Back up

CC NSIs: Scalar leptoquark model

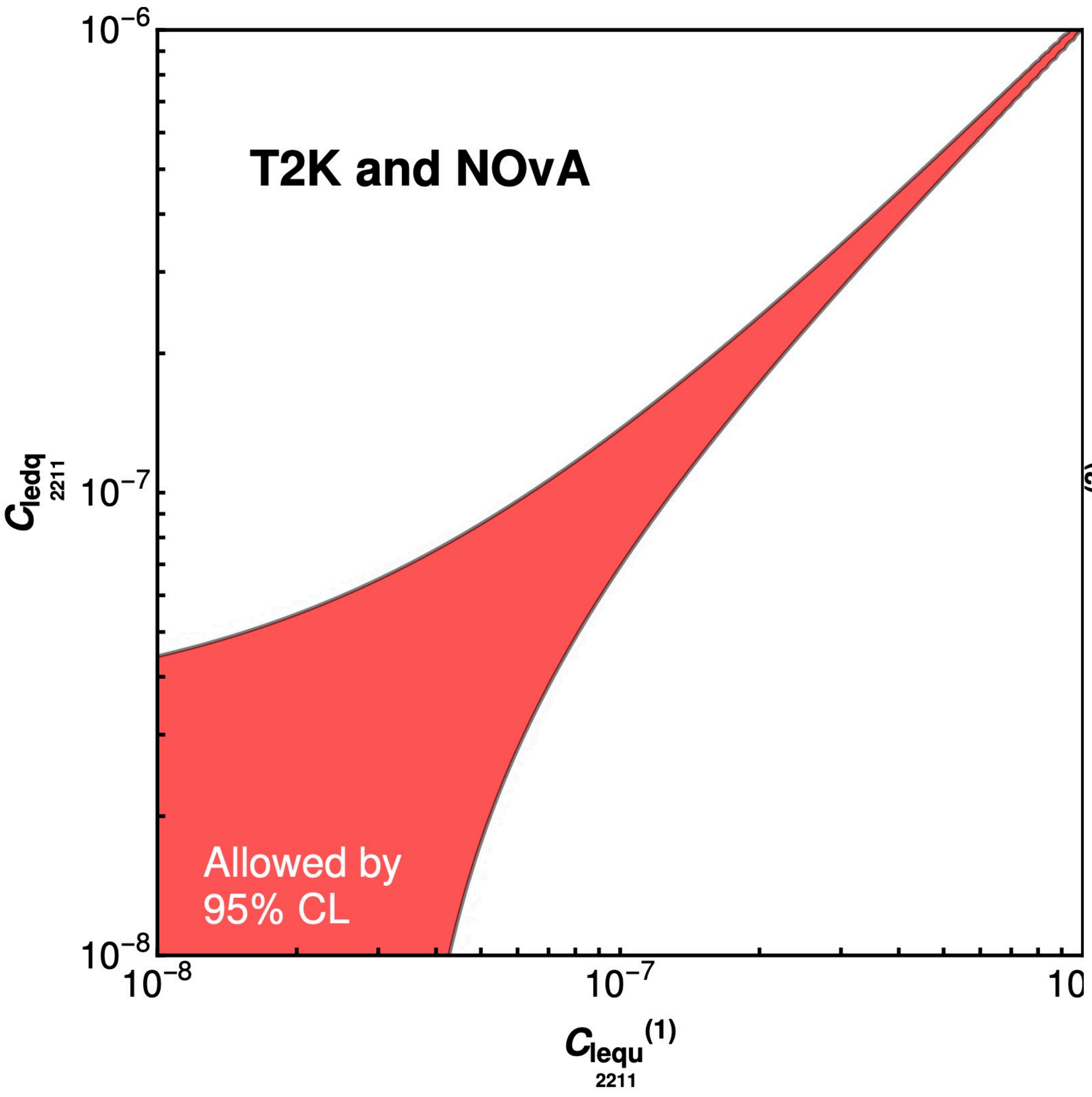
YD, H-L. Li, J. Tang, S. Vihonen, J-H. Yu, JHEP 03(2021) 019

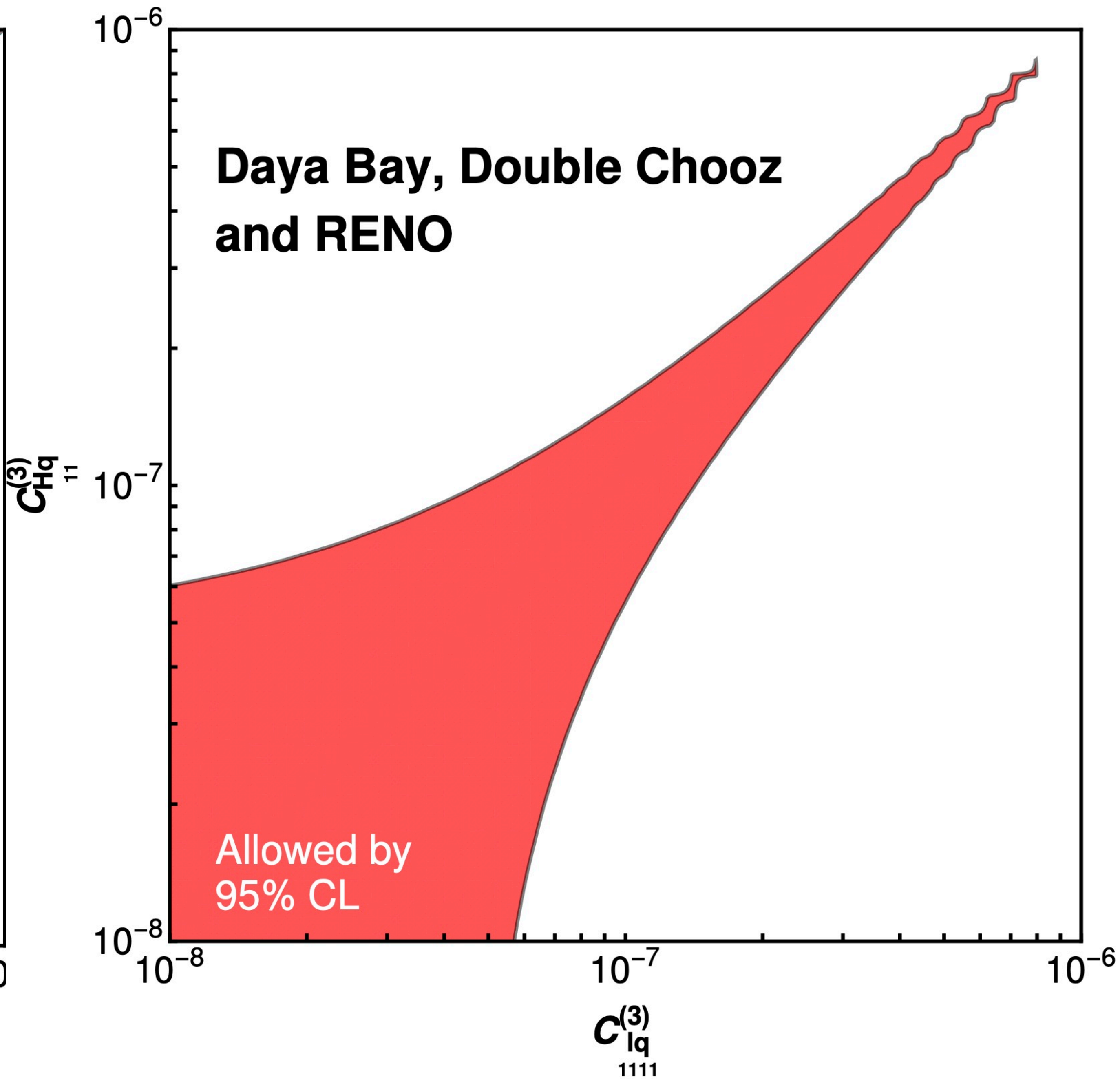
$$\mathcal{L}_{\rm LQ} = |D_\mu S|^2 - M_1^2|S|^2 - \lambda_{H1}|H|^2|S|^2 - \frac{c}{2}|S|^4 + \left((\lambda^L)_{i\alpha}\bar{q}_i^c \epsilon \ell_\alpha + (\lambda^R)_{i\alpha}\bar{u}_i^c e_\alpha\right) S_1 + \text{h.c.}$$



Multiple operators

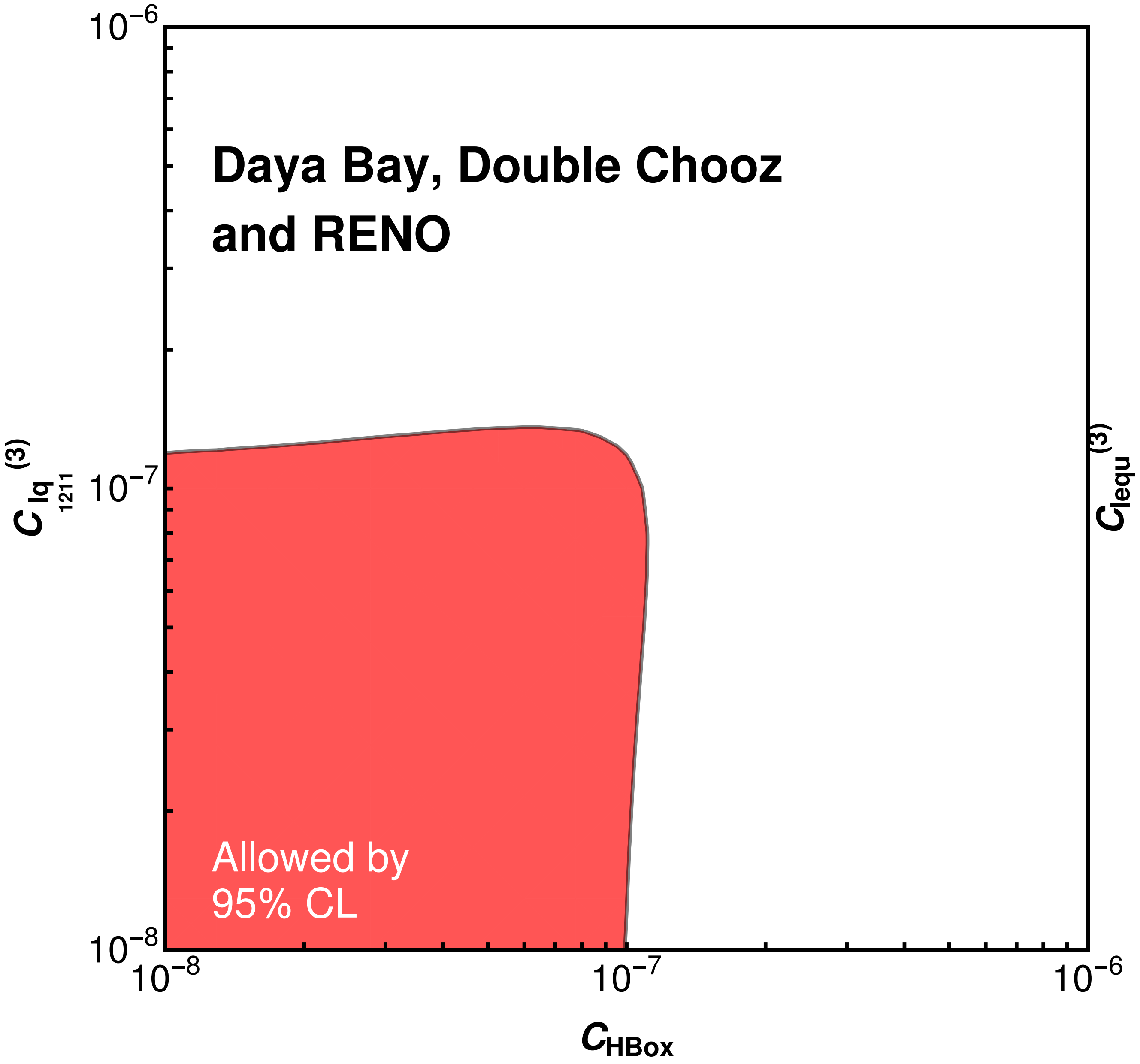
YD, H-L. Li, J. Tang, S. Vihonen, J-H. Yu, JHEP 03(2021) 019

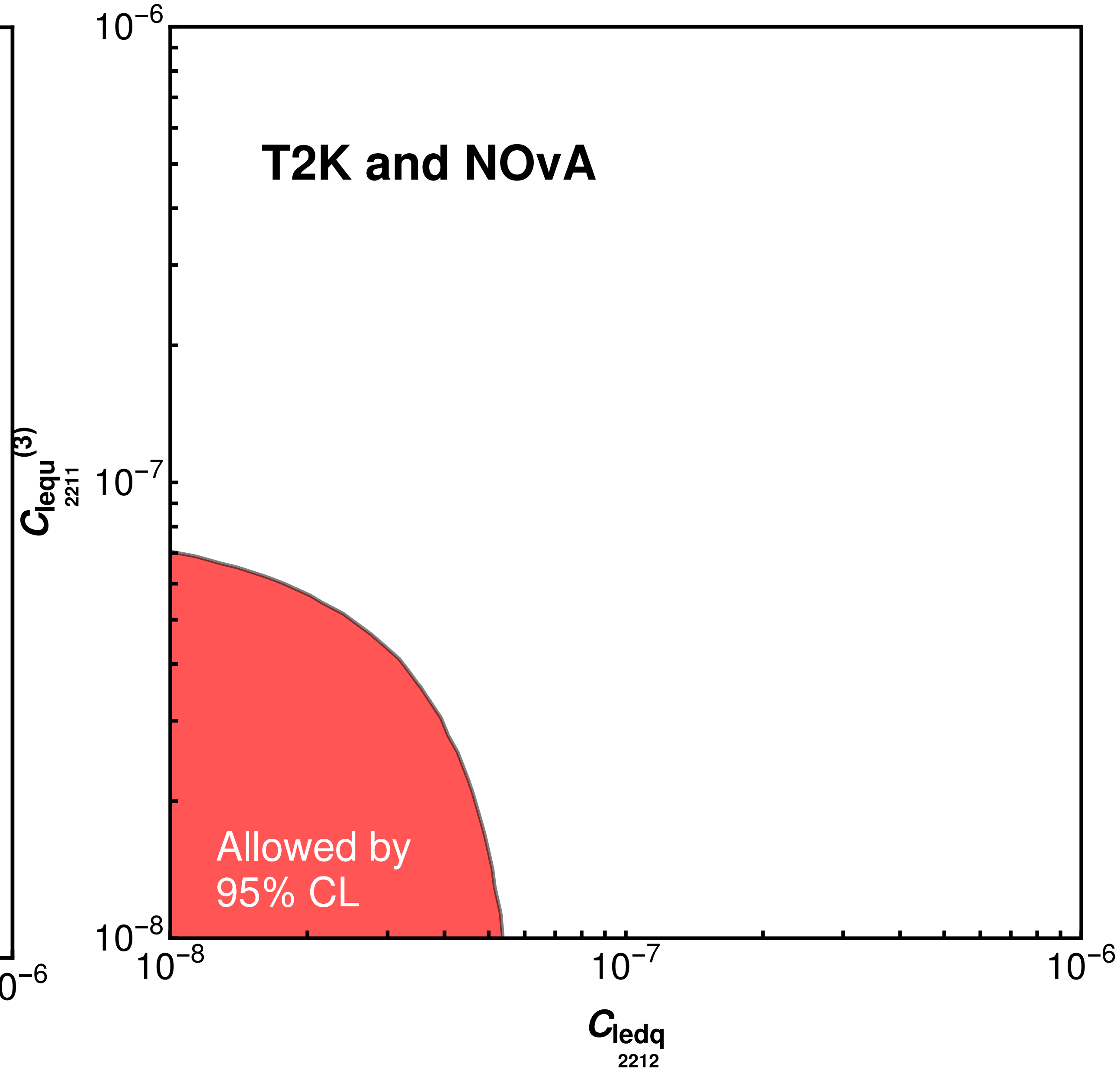




Multiple operators

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





Reactor vs LBL neutrino experiments

Reactor

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

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

LBL

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

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]
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$\epsilon_{\mu\tau}^{e,L}$	[-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]
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$\epsilon_{\mu\tau}^{e,R}$	[-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]
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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].

NC NSIs: Interference

$$\rho_{\nu-\mathrm{total}}^{\mathrm{interf.}}(\mathcal{O}_{1,e}^{(6)}) \simeq + \frac{256\sqrt{2}C_{1,e}^{(6)}G_F \sin^2\theta_W T_\gamma^9}{\pi^5\Lambda^2},$$

$$\rho_{\nu-\mathrm{total}}^{\mathrm{interf.}}(\mathcal{O}_{2,e}^{(6)}) \simeq - \frac{40\sqrt{2}C_{2,e}^{(6)}G_F T_\gamma^5 T_{\nu_e}^4}{\pi^5\Lambda^2} \times (1 + 4\sin^2\theta_W),$$

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].