4-fermion operators and their UV completion at FASERν

Yong Du

email: yongdu@itp.ac.cn

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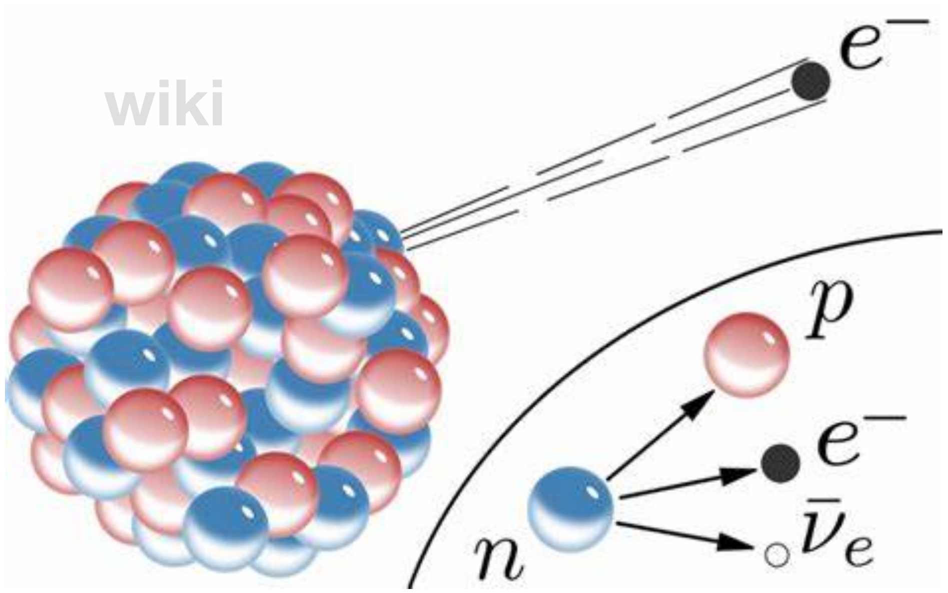
Based on work in progress: Yong Du, 2202.xxxxx

Overview

4-fermion operators have their renown in the early 1930s when Fermi wrote down the contact interactions for beta decay.



$$\sigma \sim G_F^2 E^2$$

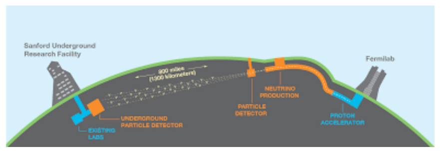
Violation of unitarity at high energies eventually helps lead to the theory for $W^{\pm}, Z$, and the SM.

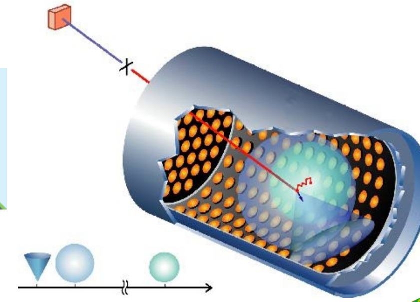
Overview

* and many more…

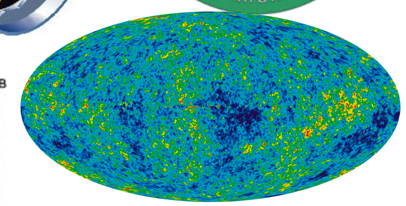
Internal – Wiki

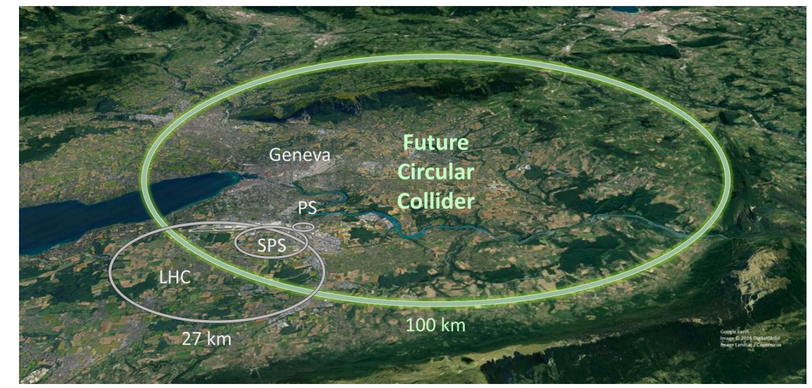
COHERENT SNS

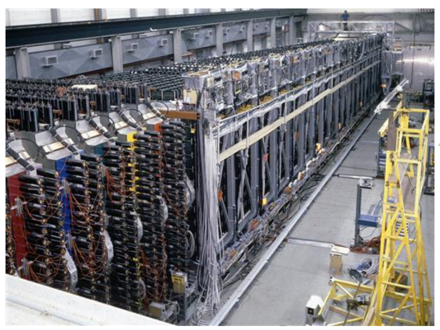


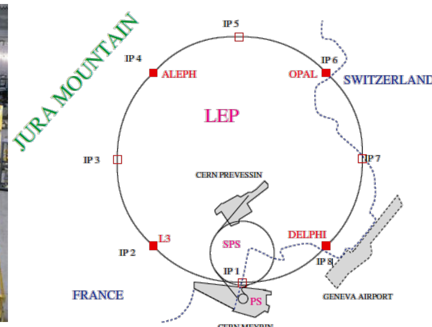


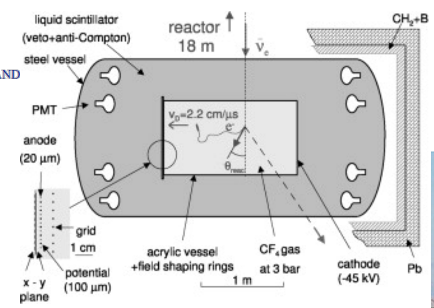
Taiwan EXperiment On NeutrinO
TEXONO
微中子 臺灣實驗

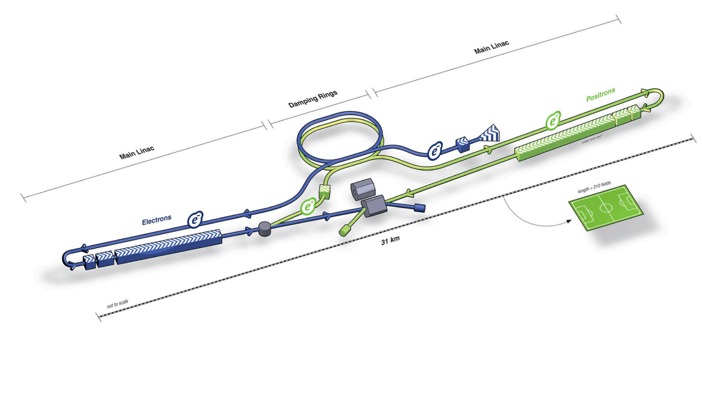


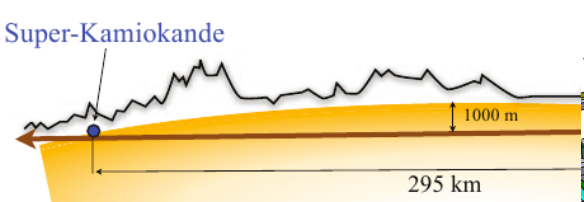


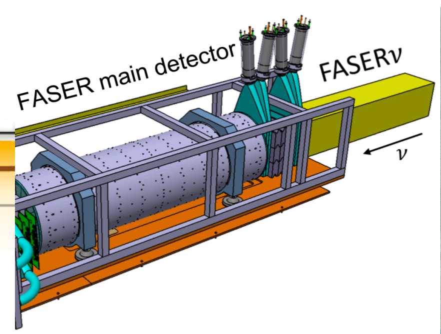


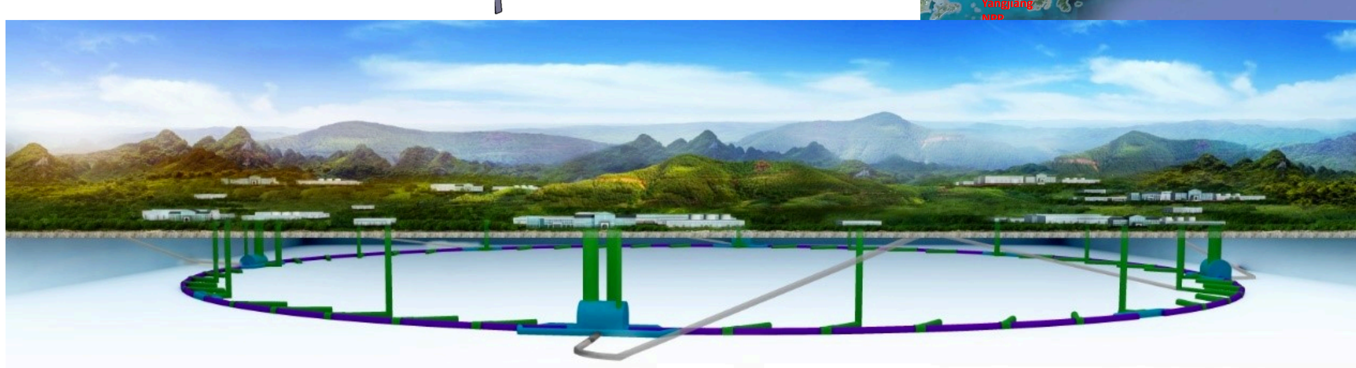


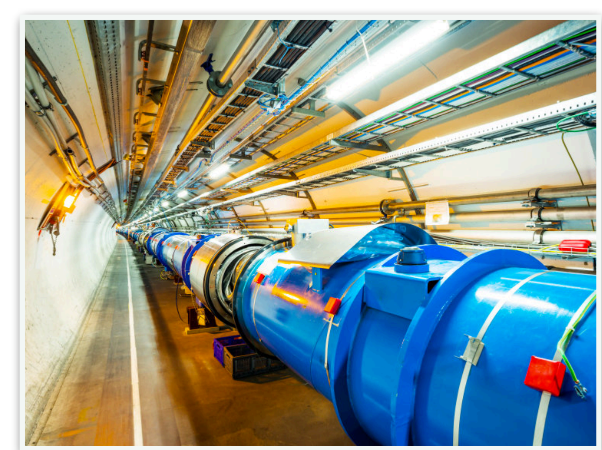












Overview

For constraints from neutrino oscillations

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Non-standard interactions in SMEFT confronted with terrestrial neutrino experiments

Yong Du,[a,b] **Hao-Lin Li,**[a] **Jian Tang,**[c] **Sampsa Vihonen**[c] **and Jiang-Hao Yu**[a,d,e,f]

[a]*CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, P.R. China*
[b]*Amherst Center for Fundamental Interactions, Physics Department, University of Massachusetts Amherst, Amherst, MA 01003 U.S.A.*
[c]*School of Physics, Sun Yat-sen University, Guangzhou 510275, China*
[d]*School of Physical Sciences, University of Chinese Academy ... Beijing 100049, P.R. China*
[e]*School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, UCAS, Hangzhou 310024, China*
[f]*International Centre for Theoretical Physics Asia-Pacific, Beijing/Hangzhou, China*

E-mail: yongdu@umass.edu, lihaolin@itp.ac.cn, tangjian5@mail.sysu.edu.cn, sampsa@mail.sysu.e...

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Neutrino non-standard interactions meet precision measurements of $N_{\rm eff}$

Yong Du[a] **and Jiang-Hao Yu**[a,b,c,d,e]

[a]*CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, P.R. China*
[b]*School of Physical Sciences, University of Chinese Academy of Sciences,*

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Exploring SMEFT Induced Non-Standard Interactions from COHERENT to Neutrino Oscillations

Yong Du,[a] **Hao-Lin Li,**[a] **Jian Tang,**[c] **Sampsa Vihonen,**[c] **Jiang-Hao Yu**[a,d,e,f,g]

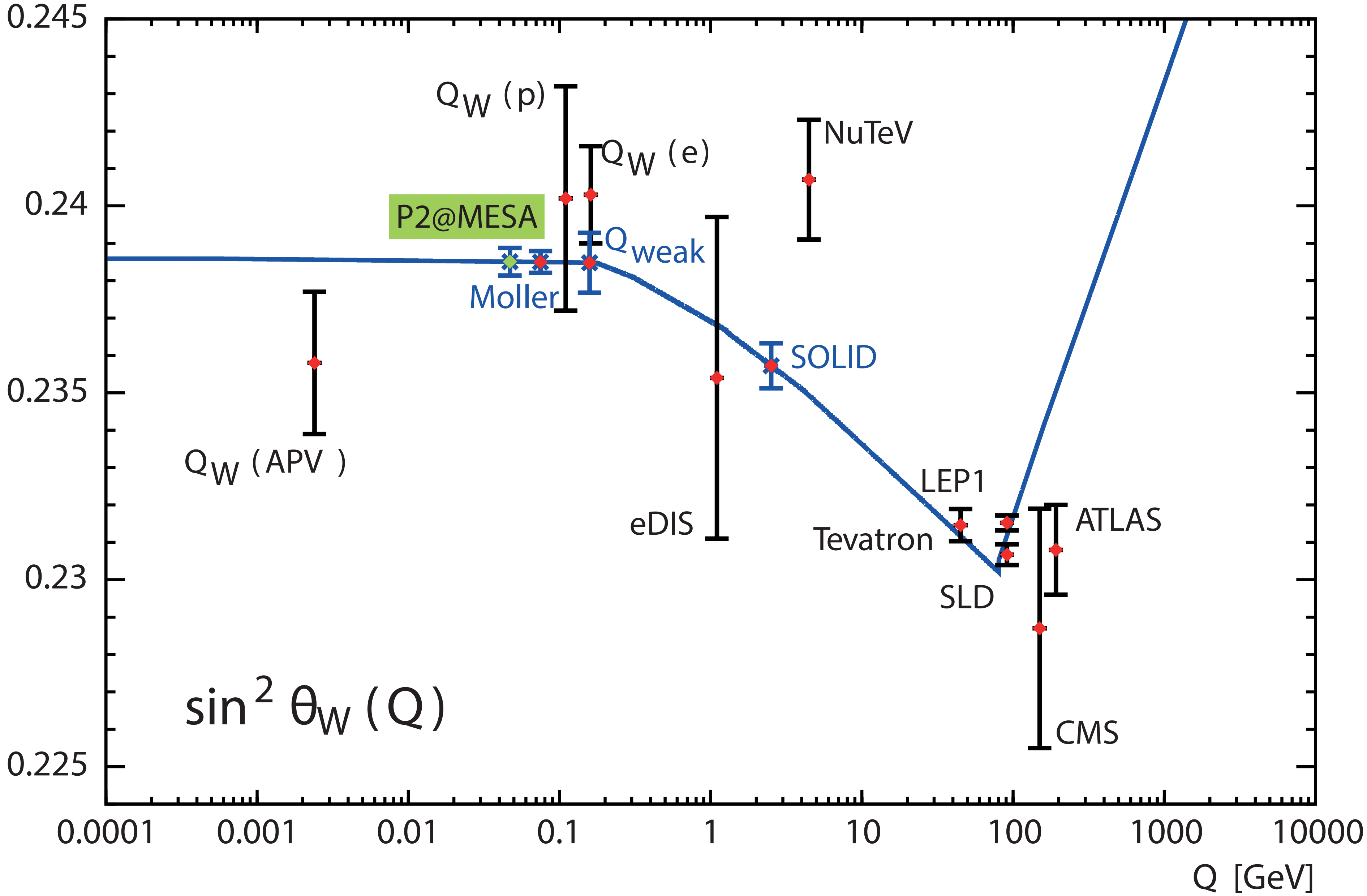
[a]*CAS Key Laboratory of Theoretical Physics, Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100190, P. R. China*
[c]*School of Physics, Sun Yat-sen University, Guangzhou 510275, China*
[d]*School of Physical Sciences, University of Chinese Academy of Sciences, Beijing 100049, P.R. China*
[e]*Center for High Energy Physics, Peking University, Beijing 100871, China*
[f]*School of Fundamental Physics and Mathematical Sciences, Hangzhou Institute for Advanced Study, UCAS, Hangzhou 310024, China*
[g]*International Centre for Theoretical Physics Asia-Pacific, Beijing/Hangzhou, China*

E-mail: yongdu@itp.ac.cn, lihaolin@itp.ac.cn, tangjian5@mail.sysu.edu.cn, sampsa@mail.sysu.edu.cn, jhyu@itp.ac.cn

ABSTRACT: We investigate the prospects of next-generation neutrino oscillation experiments DUNE, T2HK and JUNO including TAO within Standard Model Effective Field Theory (SMEFT). We also re-interpret COHERENT data in this framework. Considering both charged and neutral current neutrino Non-Standard Interactions (NSIs), we analyse dimension-6 SMEFT operators and derive lower bounds to UV scale Λ. The most powerful probe is obtained on $\mathcal{O}_{ledq_{1211}}$ with $\Lambda \gtrsim 450\,\text{TeV}$ due to the electron neutrino sample in

Overview

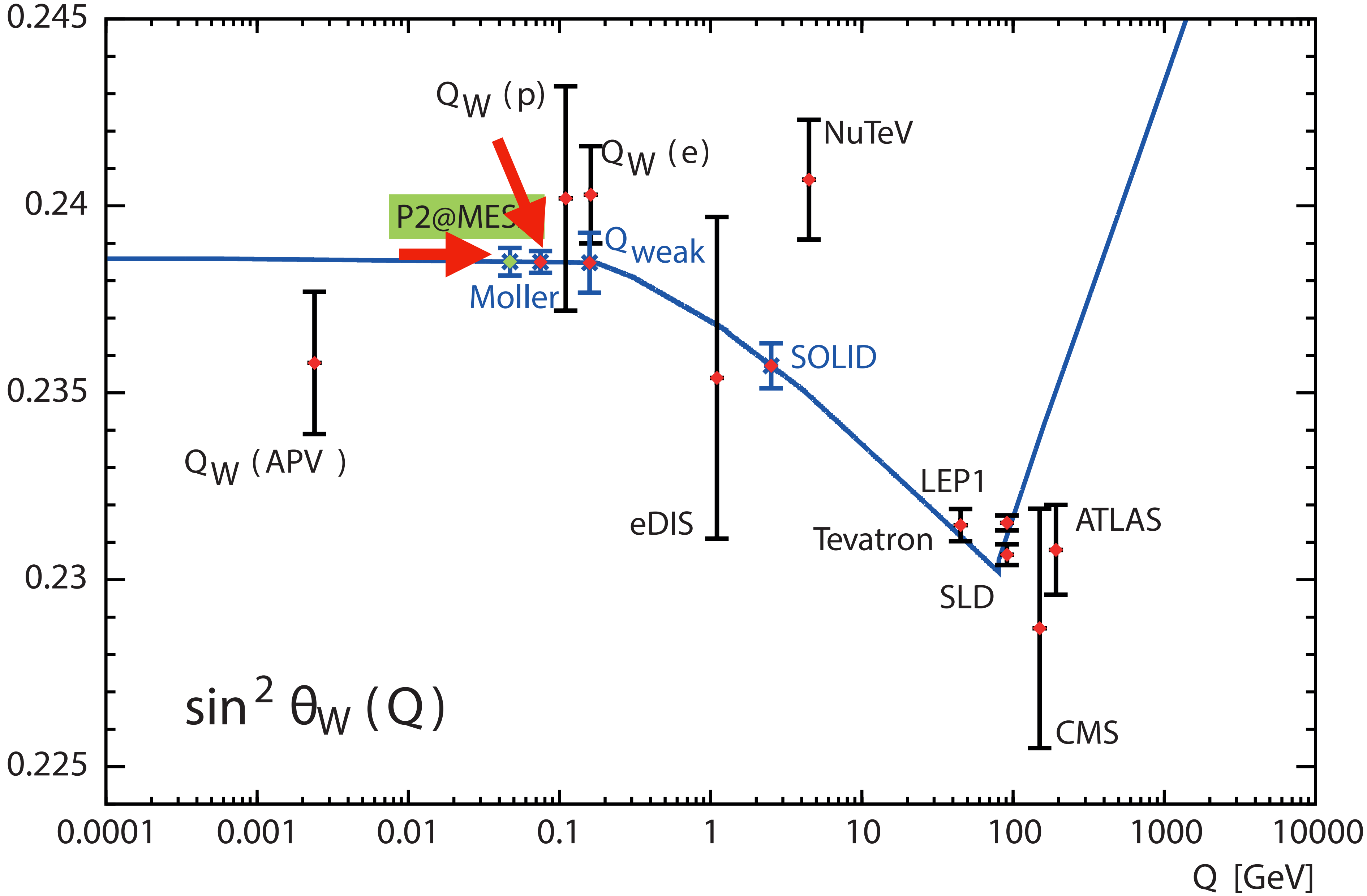
Current status and future prospects



Berger et al, 1511.03934

Overview

Current status and future prospects



Berger et al, 1511.03934

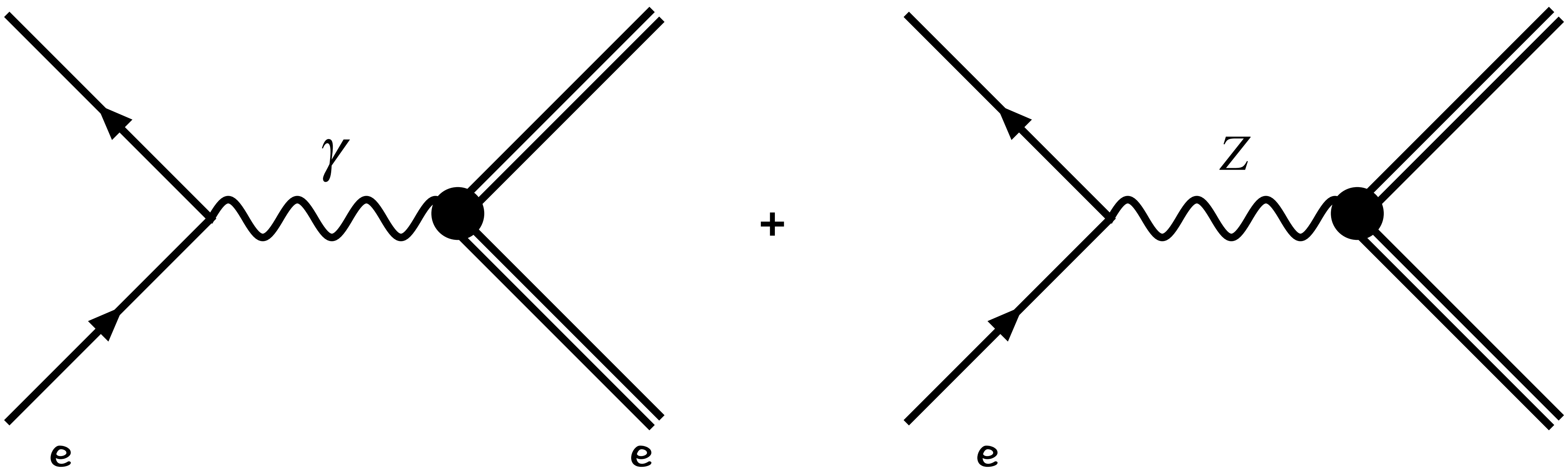
Overview

LO: Derman and Marciano, 1979

NLO: Czarnecki and Marciano, 1996

Parity-violating electron scattering (PVES) has played an essential role in establishing the SM.

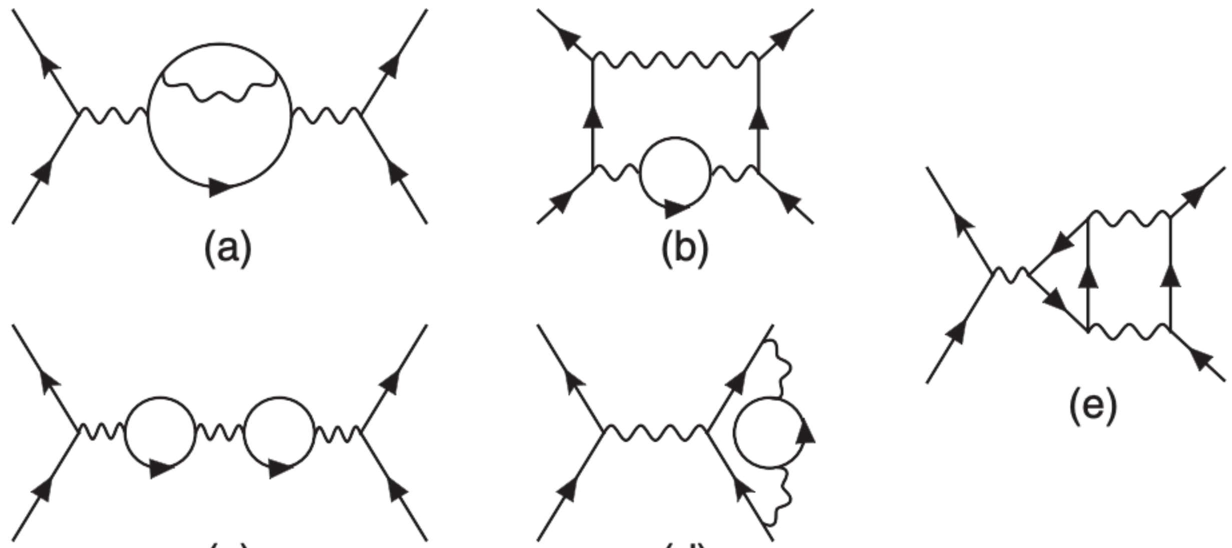
$$A_{\mathrm{PV}} = \frac{G_\mu Q^2}{\sqrt{2}\pi\alpha_{\mathrm{EM}}} \frac{1-y}{1+y^4+(1-y)^4} \left(1 - 4\sin^2\theta_W + \delta Q_W^e\right)$$



Aleksejevs et al, 2011, 2012, 2015

Overview

NNLO: **YD**, Freitas, Patel, Ramsey-Musolf, PRL 2021



Quantity	Contribution ($\times 10^{-3}$)
$1-4\sin^2\theta_W$	$+74.4$
$\Delta Q^e_{W(1,1)}$	-29.0
$\Delta Q^e_{W(1,0)}$	$+3.1$
$\Delta Q^e_{W(2,2)}$	$-0.18^{+0.0024}_{-0.0040}$
$\Delta Q^e_{W(2,1)}$	$+1.18^{+0.015}_{-0.010}$
$\Delta Q^e_{W(2,0)}$	± 0.13 (estimate)

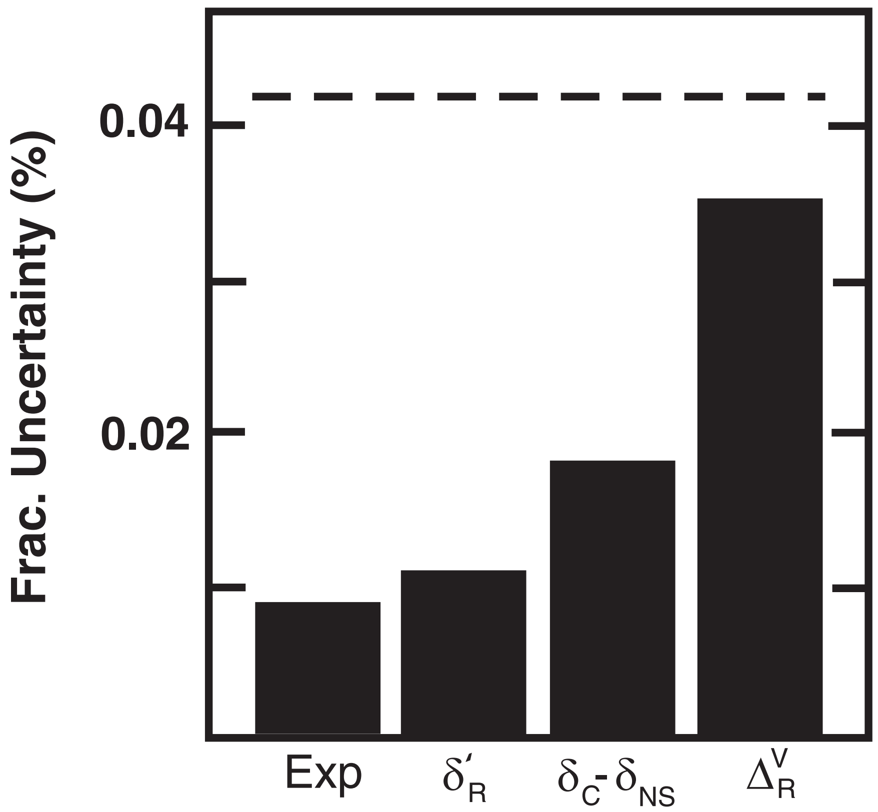
$$\Delta Q^e_{W(2,2)} + \Delta Q^e_{W(2,1)} = 1.00^{+0.012}_{-0.008} \times 10^{-3}$$

$$\Delta_{\rm exp} Q^e_W = 1.1 \times 10^{-3}$$

Overview

CKM unitarity test

Towner & Hardy, 2015



Exp. : Experiment

$\delta_{\mathrm{C}} - \delta_{\mathrm{NS}}$: Nuclear structure dependent

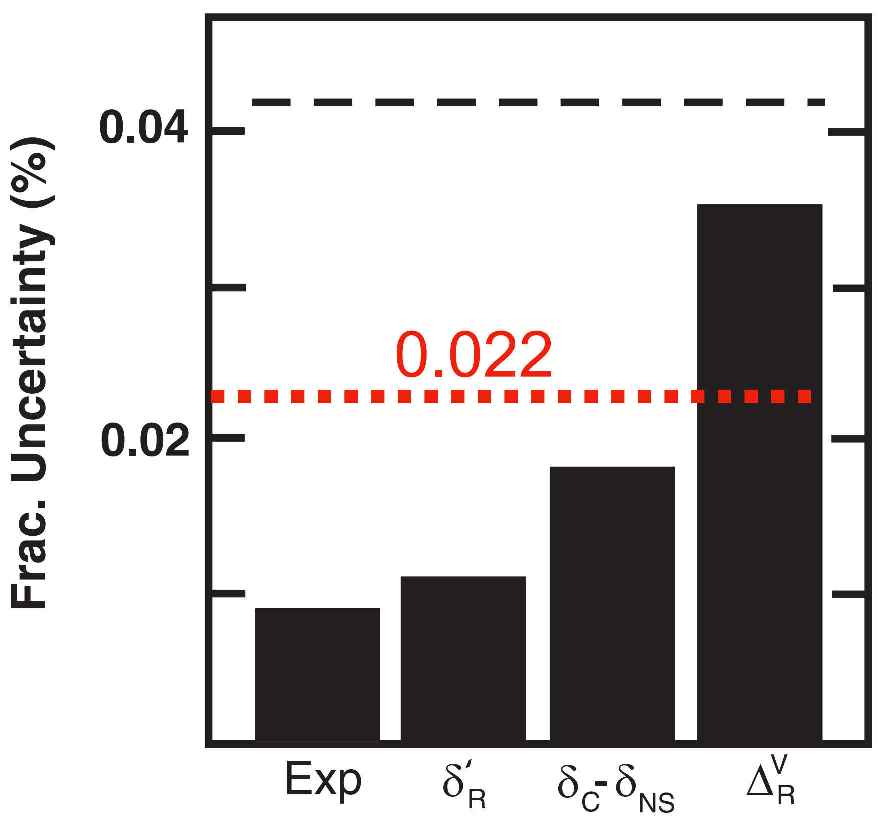
δ'_{R} : transition dependent radiative corrections

$\Delta^{\mathrm{V}}_{\mathrm{R}}$: transition independent radiative corrections

Overview

CKM unitarity test

Towner & Hardy, 2015



Exp. : Experiment

$\delta_{\rm C} - \delta_{\rm NS}$: Nuclear structure dependent

$\delta'_{\rm R}$: transition dependent radiative corrections

$\Delta^{\rm V}_{\rm R}$: transition independent radiative corrections

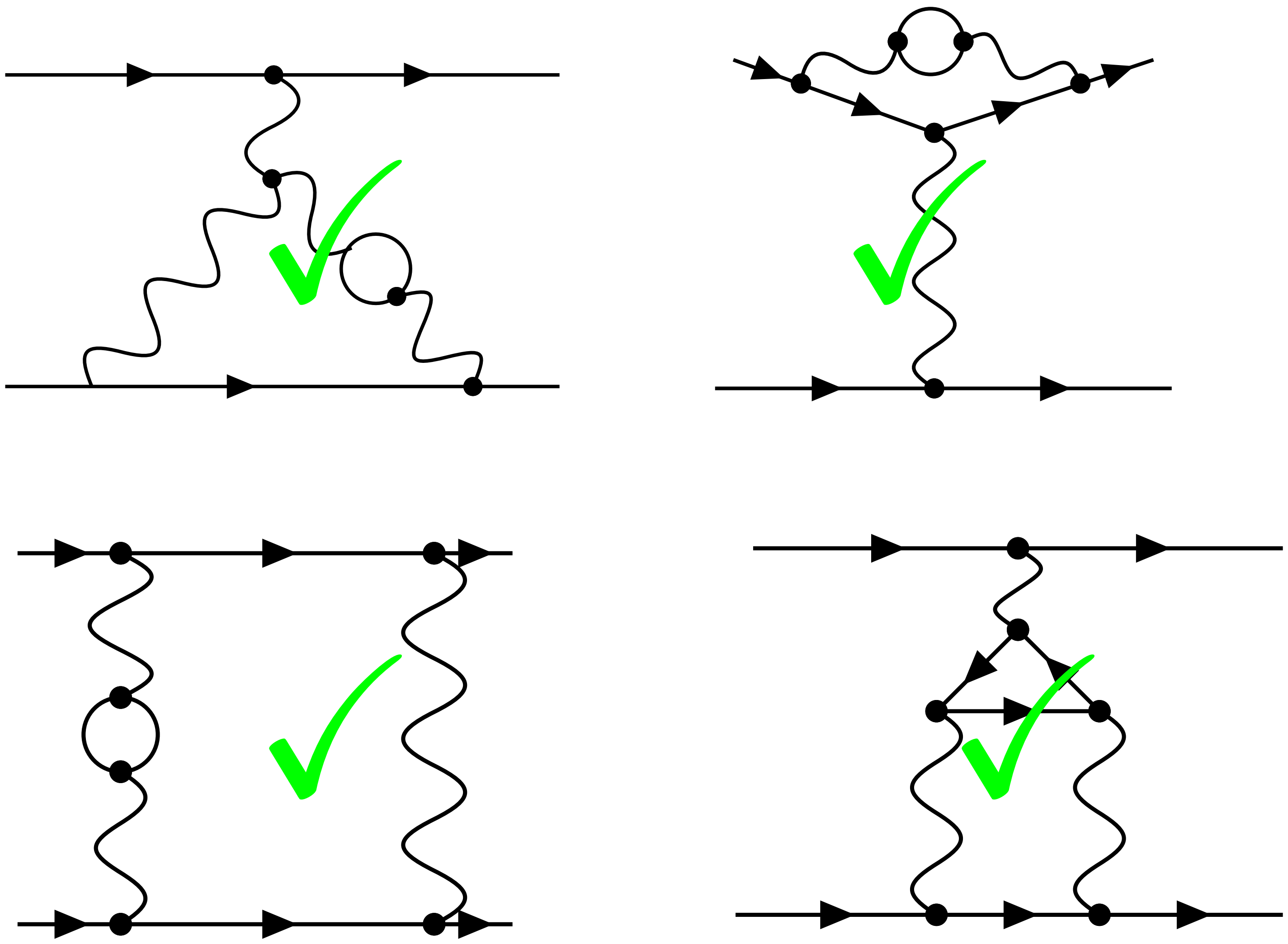
Seng, Gorchtein, Patel, Ramsey-Musolf, PRL 2018

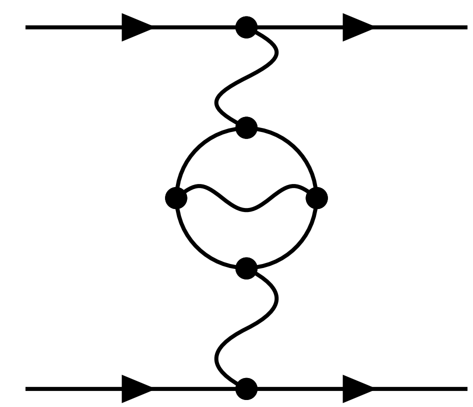
Seng, Gorchtein, Ramsey-Musolf, PRD 2019

Overview

Current status:

* in progress, with Michael Ramsey-Musolf, Jia Zhou





Trivial and not necessary.

Remaining: Non-trivial $W\gamma$ boxes on the quark line.

Overview

PVES

$$\mathcal{O}_{ee} = \frac{c_{ee}}{\Lambda^2}\left(\bar{e}\gamma_\mu e_R\right)\left(\bar{e}\gamma^\mu e_R\right)$$

Ignore flavor indices. Left-right symmetric model

$$\Lambda^{\text{Moller}} \gtrsim 10 \sim 50\,\text{TeV}$$

The MOLLER collaboration, 1411.4088

Overview

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The MOLLER collaboration, 1411.4088

Neutron decay

$$\mathcal{O}^{(3)}_{lq} = \frac{c^{(3)}_{\ell q}}{\Lambda^2}\left(\bar{\ell}\gamma_\mu \tau^I \ell\right)\left(\bar{q}\gamma^\mu \tau^I q\right)$$

Ignore flavor indices. Lepto-quark model

$$\Lambda^{\text{Neutron}} \gtrsim 7 \sim 35\,\text{TeV}$$

Gonzalez-Alonso et al, 1803.08732

Overview

PVES

$$\mathcal{O}_{ee} = \frac{c_{ee}}{\Lambda^2}\left(\bar{e}\gamma_\mu e_R\right)\left(\bar{e}\gamma^\mu e_R\right)$$

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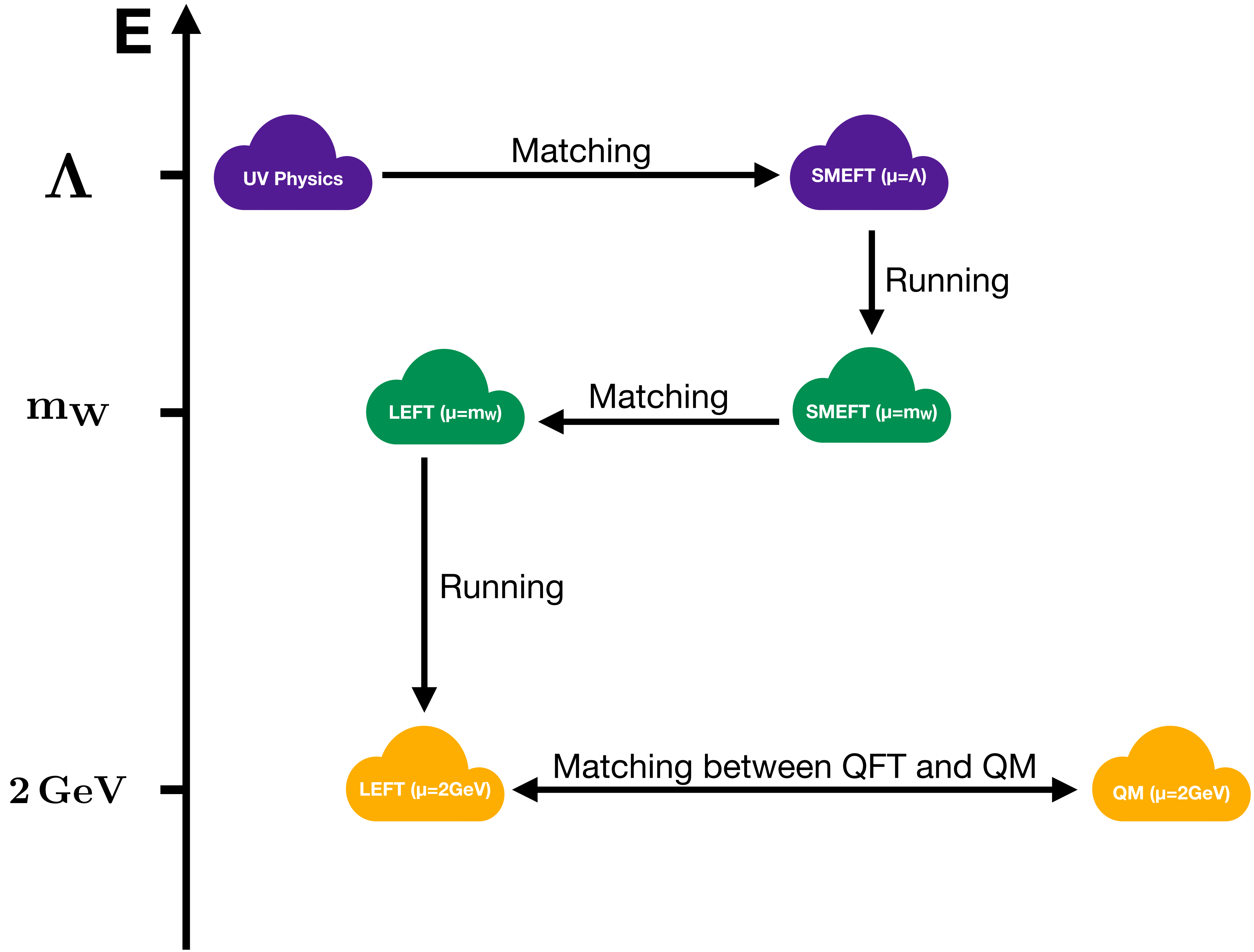
Gonzalez-Alonso et al, 1803.08732

Q: *What FASERν can add to this picture?*

Strategy

Jenkins et al, 1308.2627, 1310.4838
Alonso et al, 1312.2014



From LEFT to SMEFT

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

For example, at the weak scale and in the Warsaw-up basis,

$$\frac{V_{sk}V^*_{kt}}{v^2}[\epsilon_P^{sk}(m_Z)]_{pr} = 0.5C_{ledq,prst} - 0.5C^{(1)}_{lequ,prst}$$

p, r, s, t flavor indices
i, j, k mass indices

Jenkins et al, 1709.04486 (JHEP)

From LEFT to SMEFT

$$\frac{V_{sk}V_{kt}^*}{v^2}[\epsilon_P^{sk}(m_Z)]_{pr} = 0.5C_{ledq,prst} - 0.5C^{(1)}_{lequ,prst}$$

Running effects from QCD loops are very important for these semi-leptonic operators (3-loop QCD + 1-loop EW) Gonzalaz-Alonso et al, 1706.00410 (PLB)

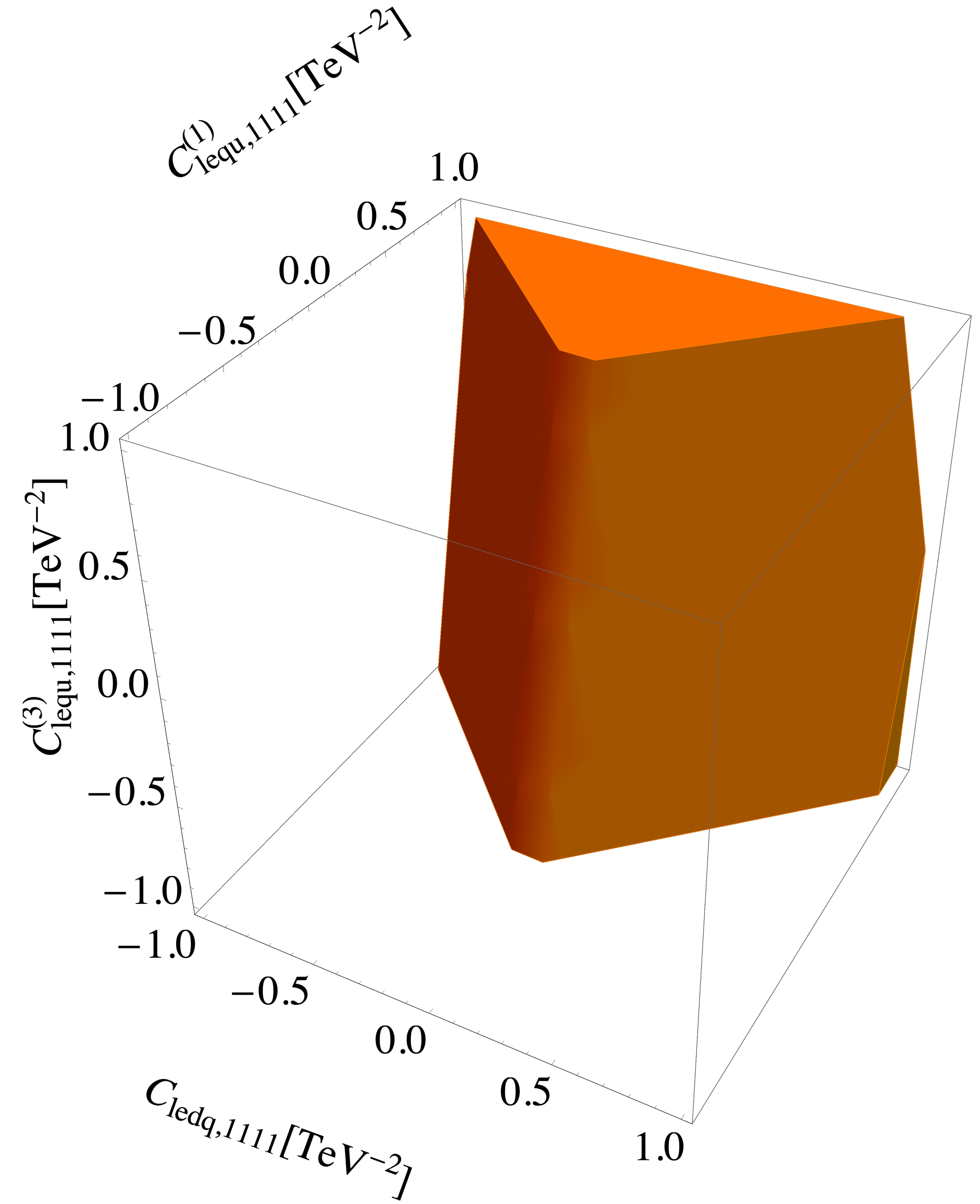
$$\begin{pmatrix} \epsilon_L \\ \epsilon_R \\ \epsilon_S \\ \epsilon_P \\ \epsilon_T \end{pmatrix}_{(\mu = 2\ \mathrm{GeV})} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1.0046 & 0 & 0 & 0 \\ 0 & 0 & 1.72 & 2.46 \times 10^{-6} & -0.0242 \\ 0 & 0 & 2.46 \times 10^{-6} & 1.72 & -0.0242 \\ 0 & 0 & -2.17 \times 10^{-4} & -2.17 \times 10^{-4} & 0.825 \end{pmatrix} \begin{pmatrix} \epsilon_L \\ \epsilon_R \\ \epsilon_S \\ \epsilon_P \\ \epsilon_T \end{pmatrix}_{(\mu = Z)}$$

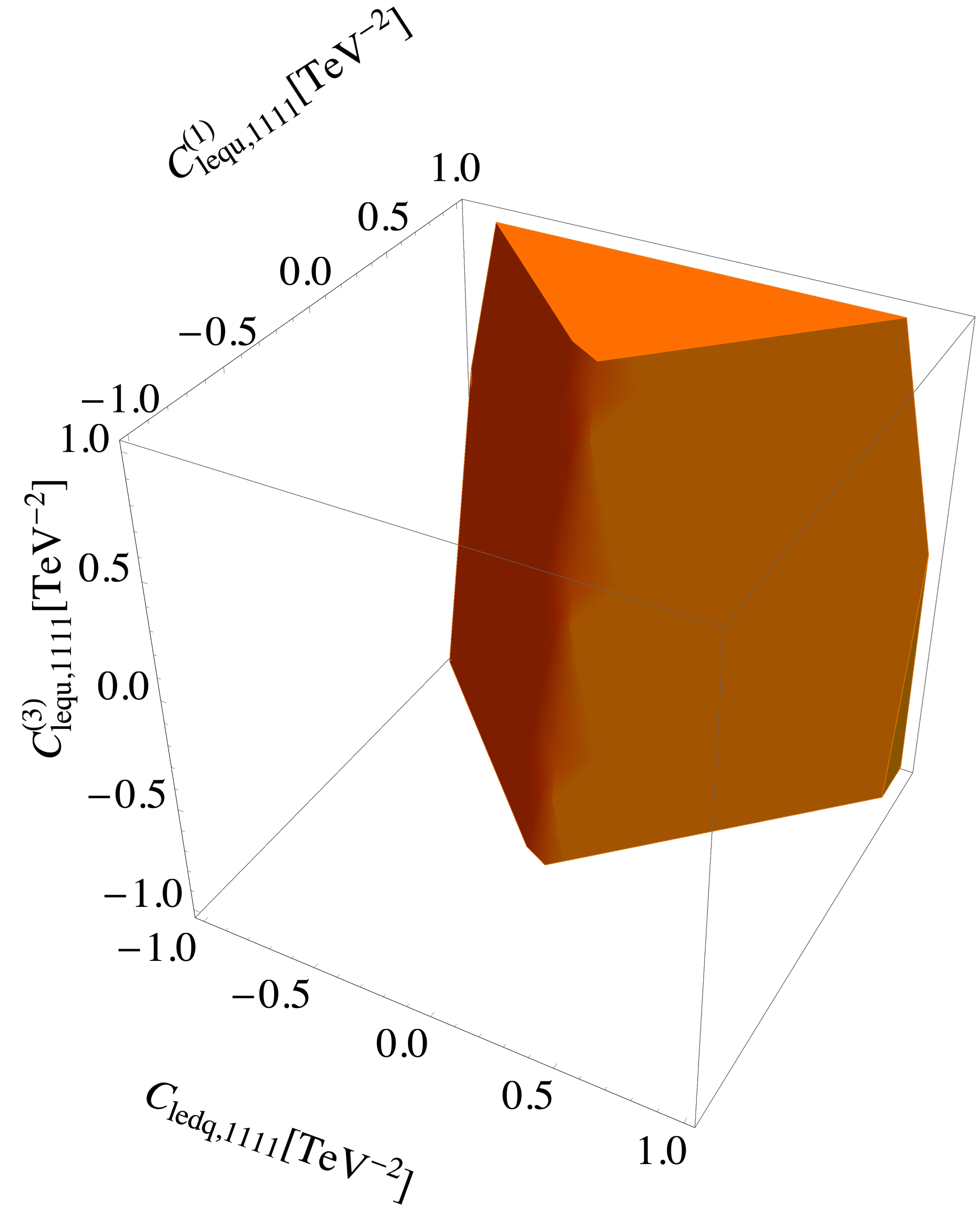
Then one can match the LEFT onto the SMEFT (at 1TeV for example)

$$\frac{V_{sk}V_{kt}^*}{v^2}[\epsilon_P^{sk}(2\,\mathrm{GeV})]_{pr} = 1.0234C_{ledq,prst} - 1.03218C^{(1)}_{\ell equ,prst} + 0.205515C^{(3)}_{\ell equ,prst}$$

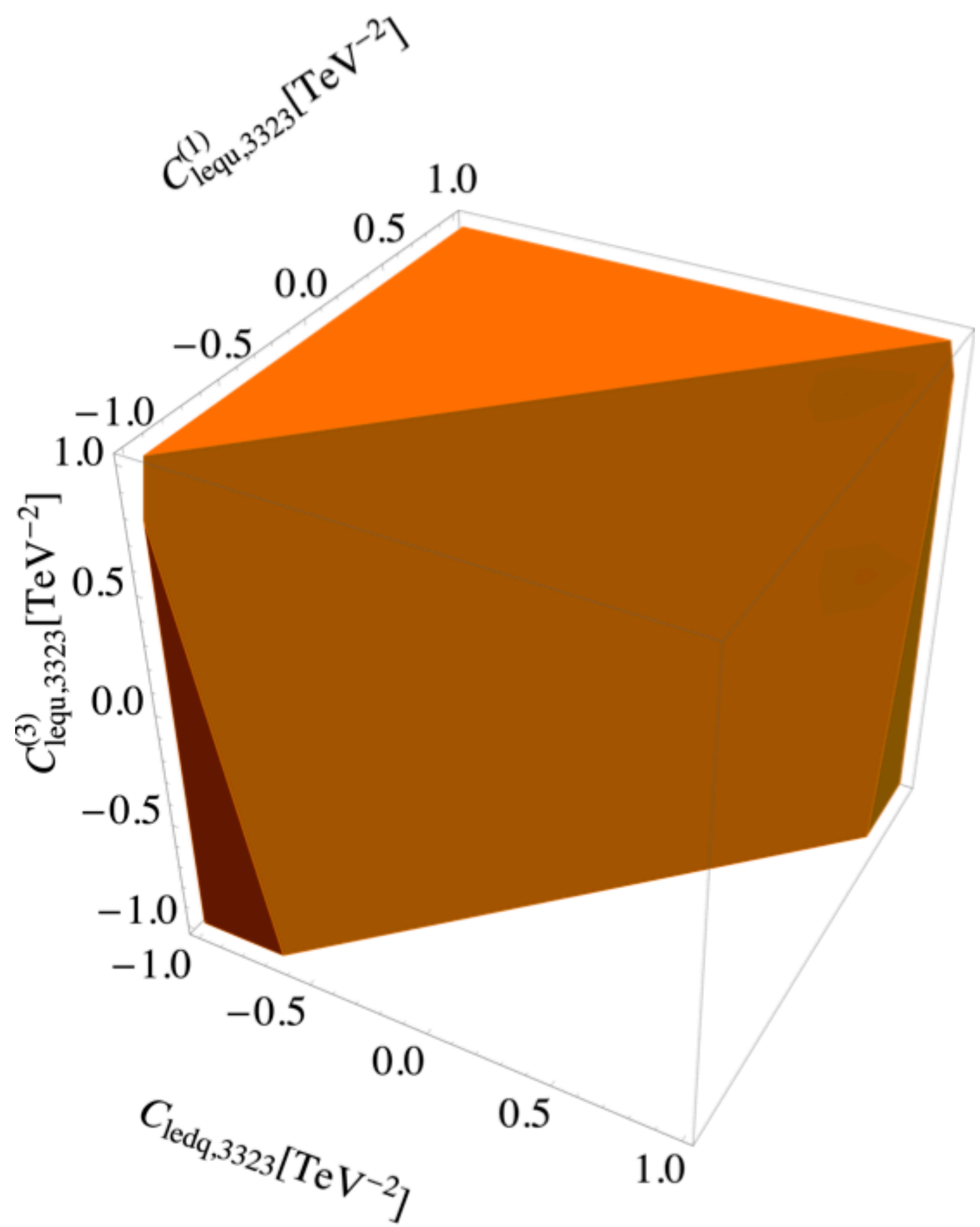
Results

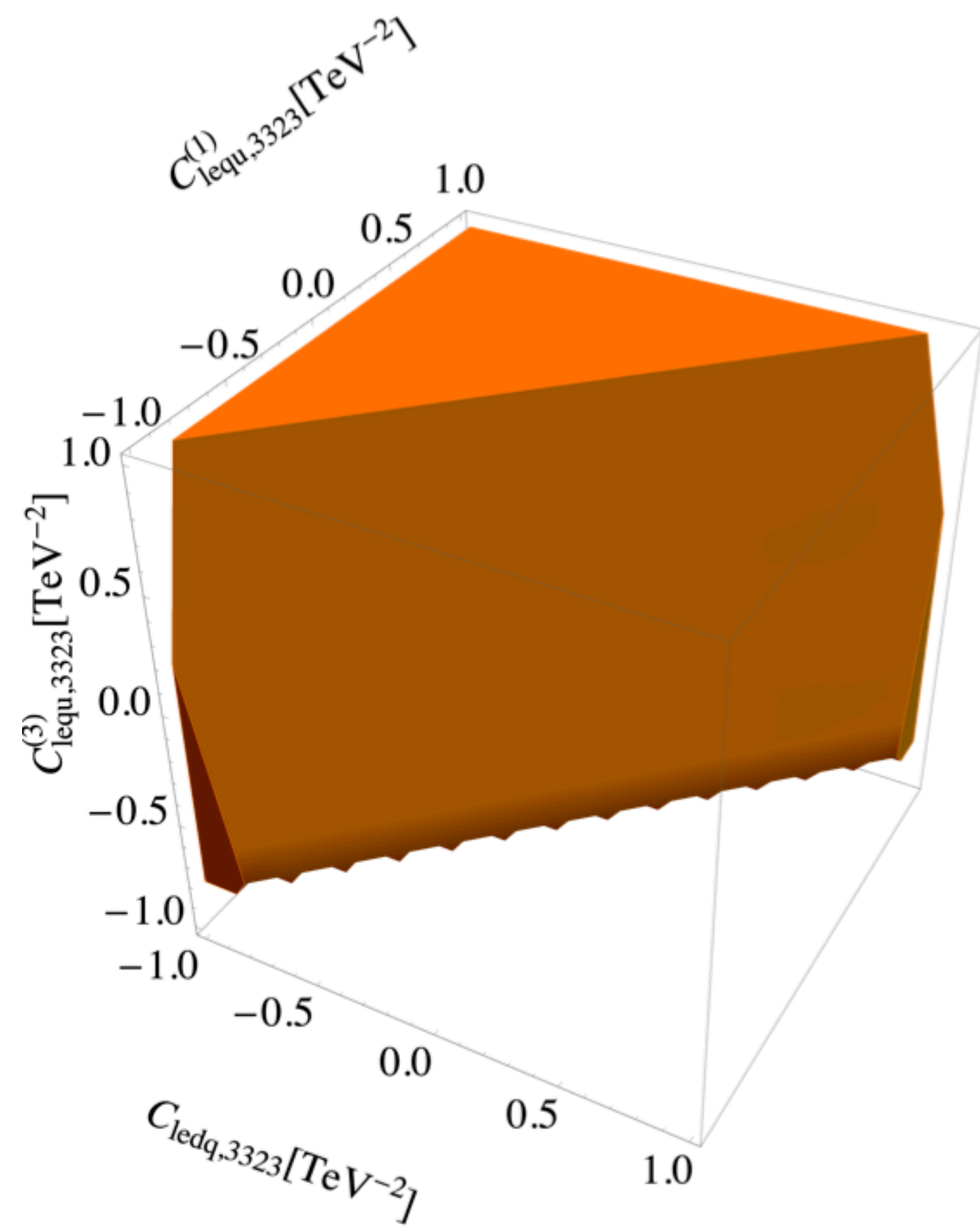
For neutrino production through meson decay and neutrino detection through DIS, see the talk by Zahra Tabrizi during the 2nd FPF meeting





Results


$C^{(1)}_{\text{lequ},3323}[\text{TeV}^{-2}]$
$C^{(3)}_{\text{lequ},3323}[\text{TeV}^{-2}]$
$C_{\text{ledq},3323}[\text{TeV}^{-2}]$
1.0
0.5
0.0
−0.5
−1.0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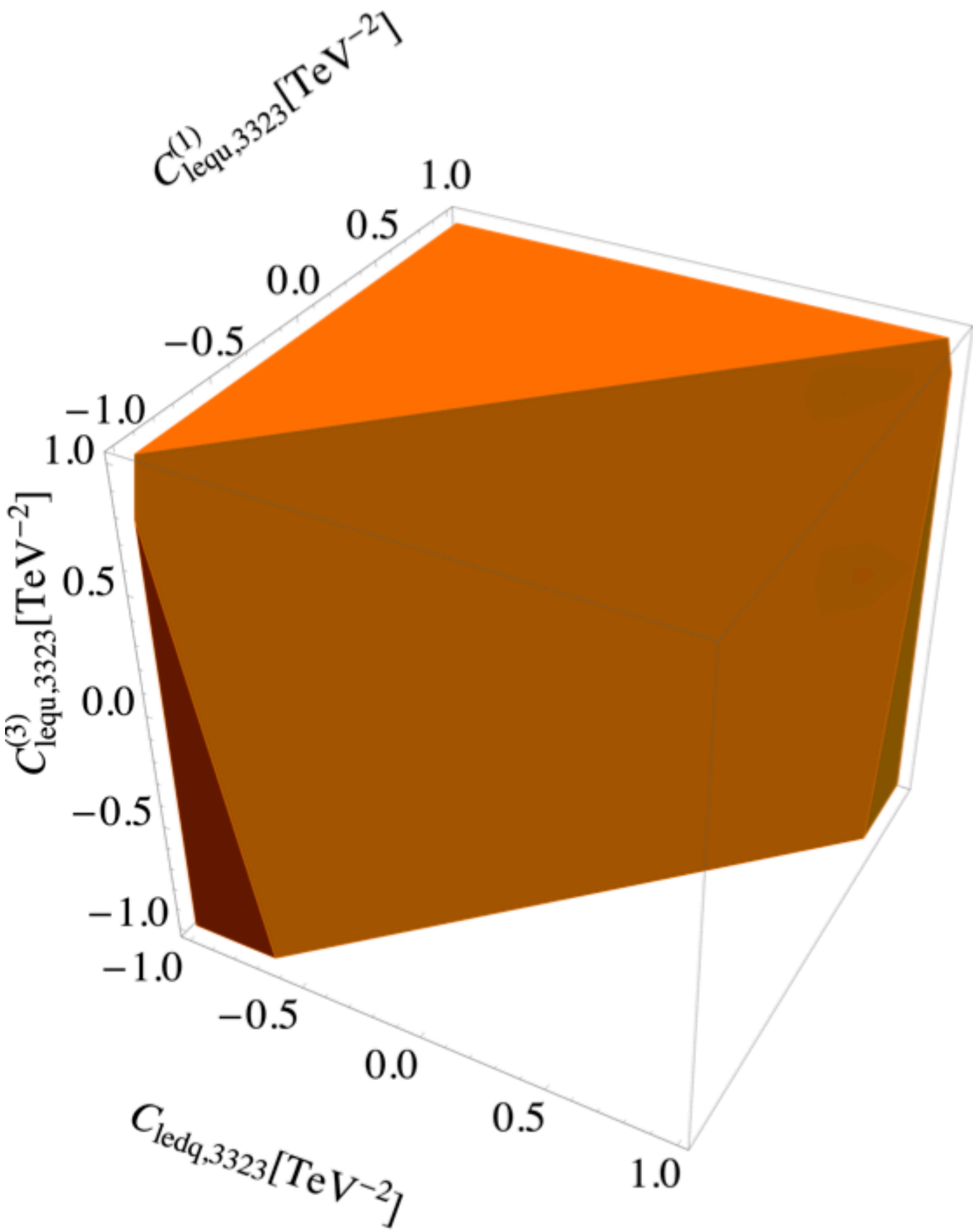
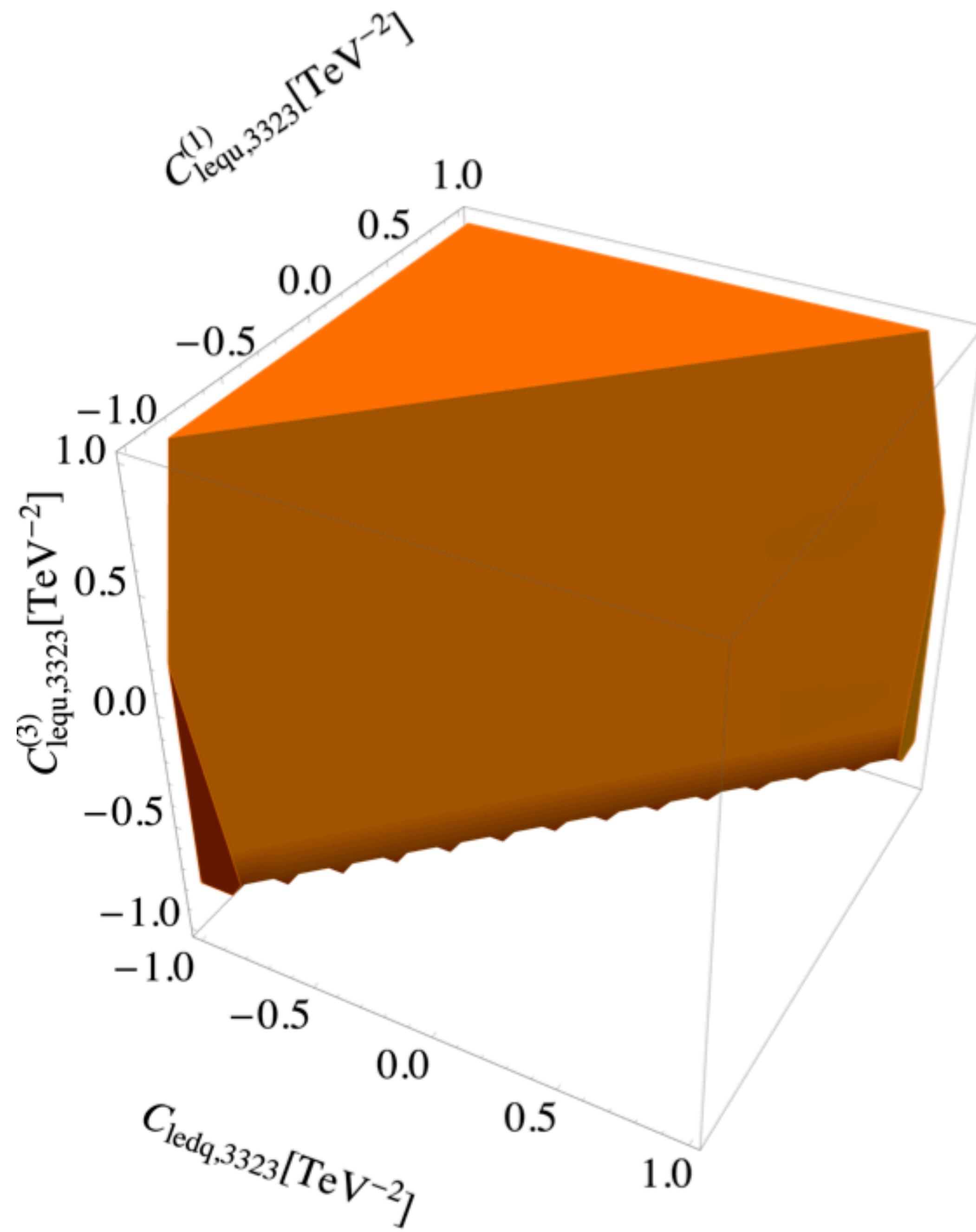
Results



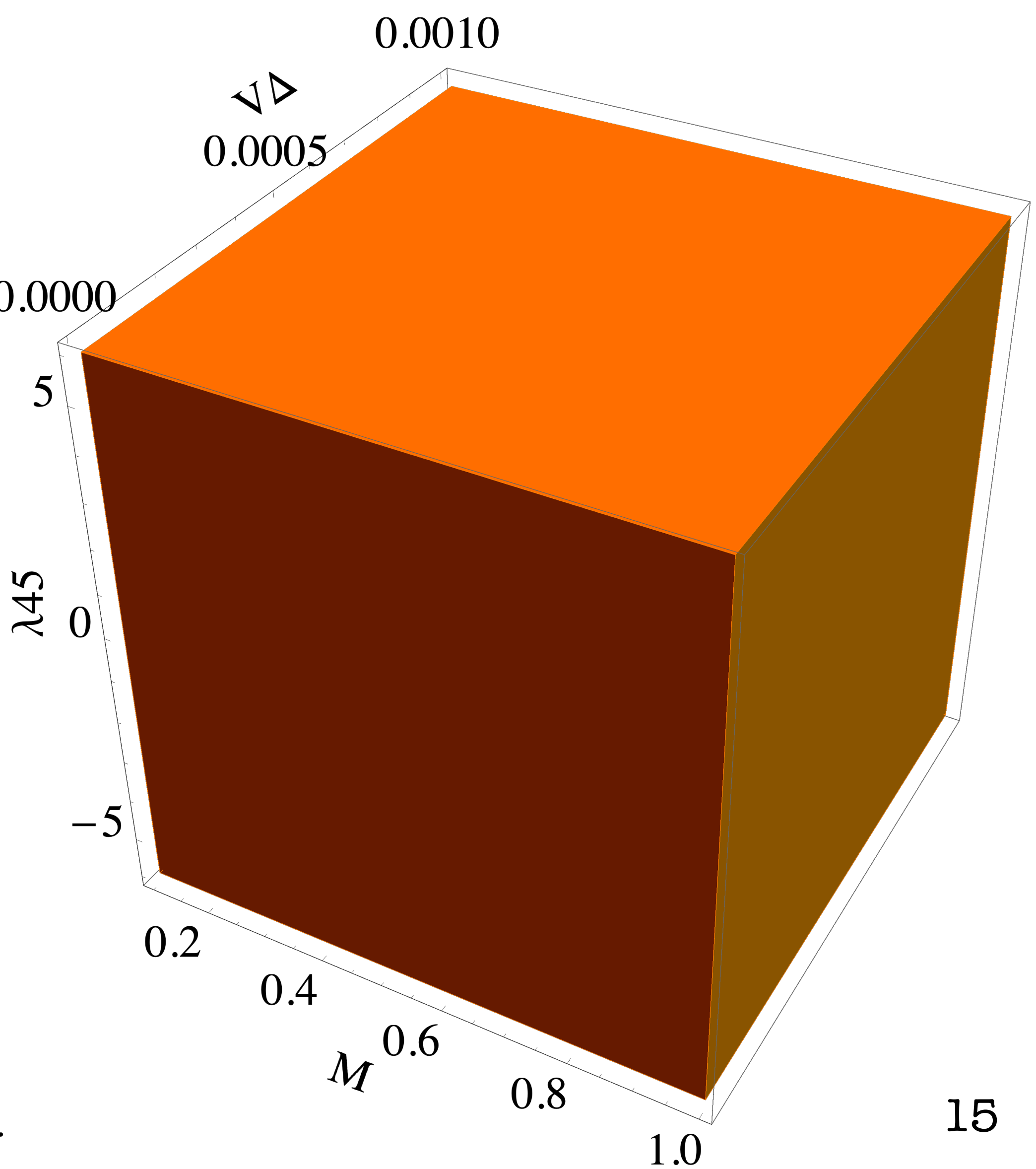


Q: Constraints on the UV?

Results

Tree-level seesaw models? Not good.

Type: $\psi_L\psi_R\psi_R\psi_L$ and $\psi_L\psi_R\psi_L\psi_R$			
Operator	Type-I	Type-II	Type-III
$\mathcal{O}_{ledq,prst}$	$-\frac{\bar{Y}_d^{ts}\bar{Y}_\nu^{uv}\left(3Y_e^{ur}Y_\nu^{pv}-2Y_e^{pr}Y_\nu^{uv}\right)}{6M^2}$	$\frac{\mu^2 Y_e^{pr}\bar{Y}_d^{ts}}{2M^4}$	$\frac{Y_\Sigma^{uv}\bar{Y}_d^{ts}\left(2Y_e^{pr}\bar{Y}_\Sigma^{uv}+3Y_e^{vr}\bar{Y}_\Sigma^{up}\right)}{2M^2}$
$\mathcal{O}^{(1)}_{quqd,prst}$	$\frac{Y_d^{st}Y_u^{pr}Y_\nu^{uv}\bar{Y}_\nu^{uv}}{3M^2}$	$\frac{\mu^2 Y_d^{st}Y_u^{pr}}{2M^4}$	$\frac{Y_d^{st}Y_u^{pr}Y_\Sigma^{uv}\bar{Y}_\Sigma^{uv}}{M^2}$
$\mathcal{O}^{(1)}_{lequ,prst}$	$\frac{Y_u^{st}\bar{Y}_\nu^{uv}\left(3Y_e^{ur}Y_\nu^{pv}-2Y_e^{pr}Y_\nu^{uv}\right)}{6M^2}$	$-\frac{\mu^2 Y_e^{pr}Y_u^{st}}{2M^4}$	$-\frac{Y_u^{st}Y_\Sigma^{uv}\left(2Y_e^{pr}\bar{Y}_\Sigma^{uv}+3Y_e^{vr}\bar{Y}_\Sigma^{up}\right)}{2M^2}$



YD, Li, Yu, 2201.04646

Results

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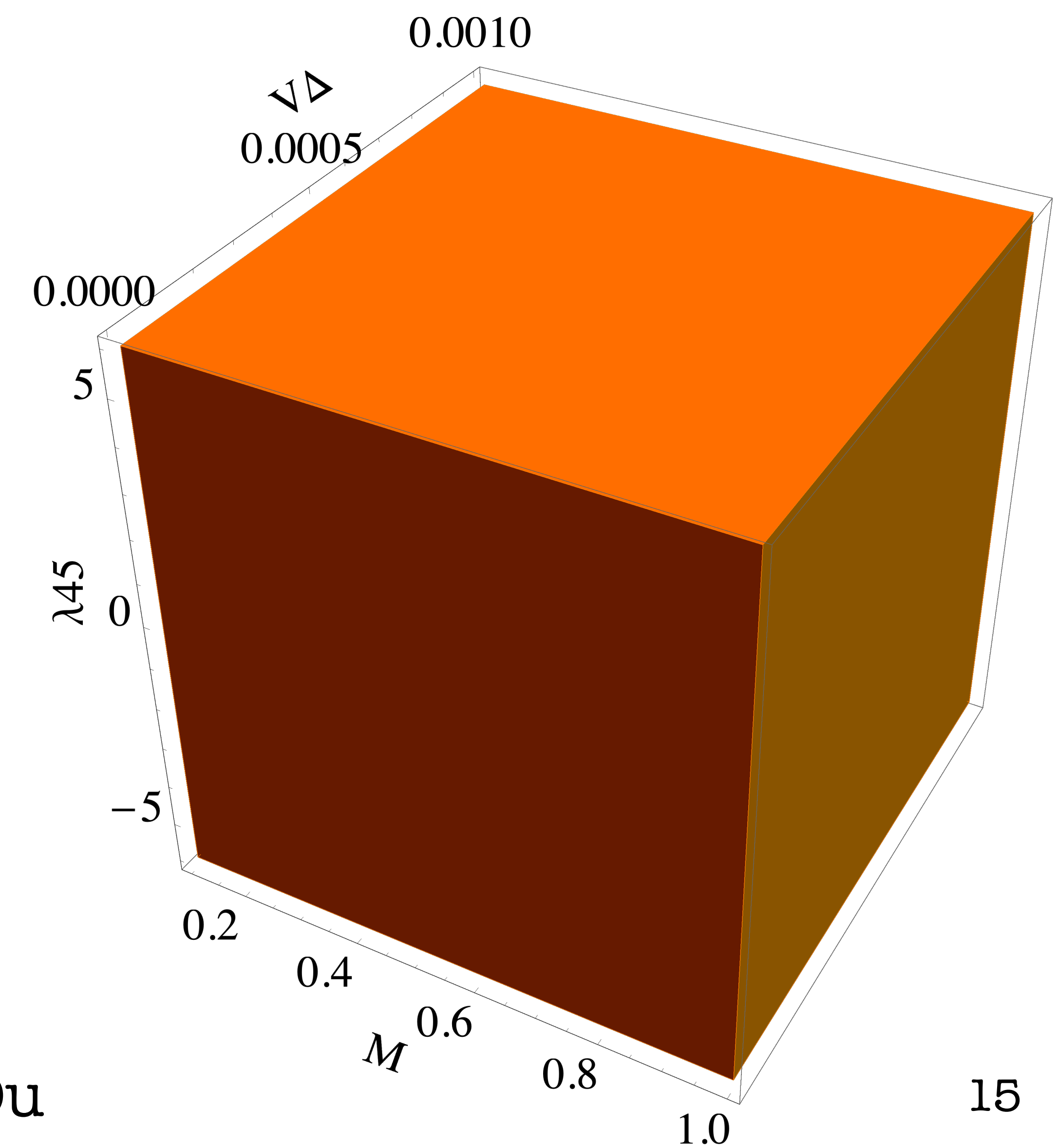
Type: $\psi_L\psi_R\psi_R\psi_L$ and $\psi_L\psi_R\psi_L\psi_R$			
Operator	Type-I	Type-II	Type-III
$\mathcal{O}_{ledq,prst}$	$-\frac{\bar{Y}_d^{ts}\bar{Y}_\nu^{uv}\left(3Y_e^{ur}Y_\nu^{pv}-2Y_e^{pr}Y_\nu^{uv}\right)}{6M^2}$	$\frac{\mu^2 Y_e^{pr}\bar{Y}_d^{ts}}{2M^4}$	$\frac{Y_\Sigma^{uv}\bar{Y}_d^{ts}\left(2Y_e^{pr}\bar{Y}_\Sigma^{uv}+3Y_e^{vr}\bar{Y}_\Sigma^{up}\right)}{2M^2}$
$\mathcal{O}^{(1)}_{quqd,prst}$	$\frac{Y_d^{st}Y_u^{pr}Y_\nu^{uv}\bar{Y}_\nu^{uv}}{3M^2}$	$\frac{\mu^2 Y_d^{st}Y_u^{pr}}{2M^4}$	$\frac{Y_d^{st}Y_u^{pr}Y_\Sigma^{uv}\bar{Y}_\Sigma^{uv}}{M^2}$
$\mathcal{O}^{(1)}_{lequ,prst}$	$\frac{Y_u^{st}\bar{Y}_\nu^{uv}\left(3Y_e^{ur}Y_\nu^{pv}-2Y_e^{pr}Y_\nu^{uv}\right)}{6M^2}$	$-\frac{\mu^2 Y_e^{pr}Y_u^{st}}{2M^4}$	$-\frac{Y_u^{st}Y_\Sigma^{uv}\left(2Y_e^{pr}\bar{Y}_\Sigma^{uv}+3Y_e^{vr}\bar{Y}_\Sigma^{up}\right)}{2M^2}$



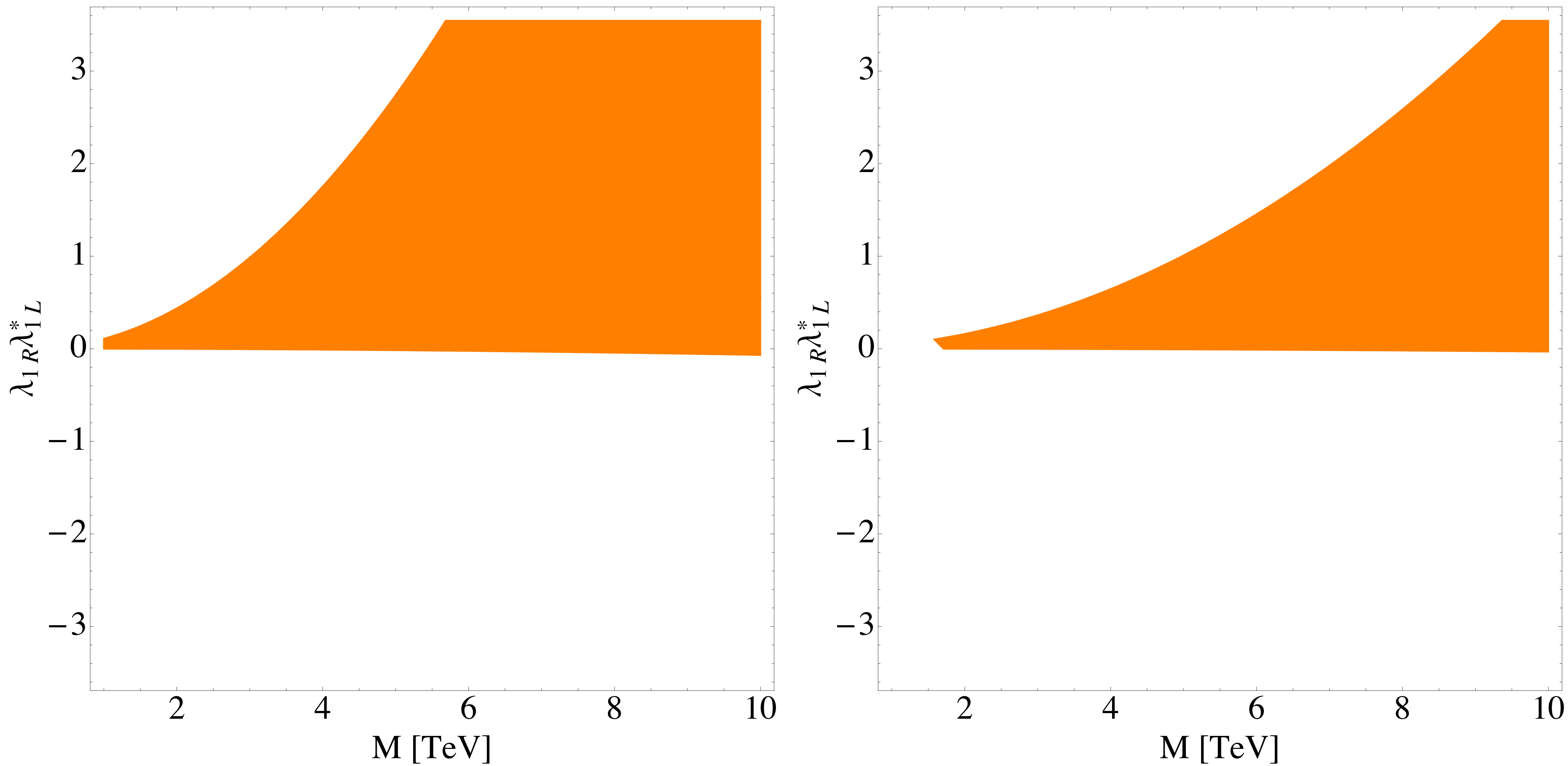
YD, Li, Yu, 2201.04646

Leptoquark models?

Results

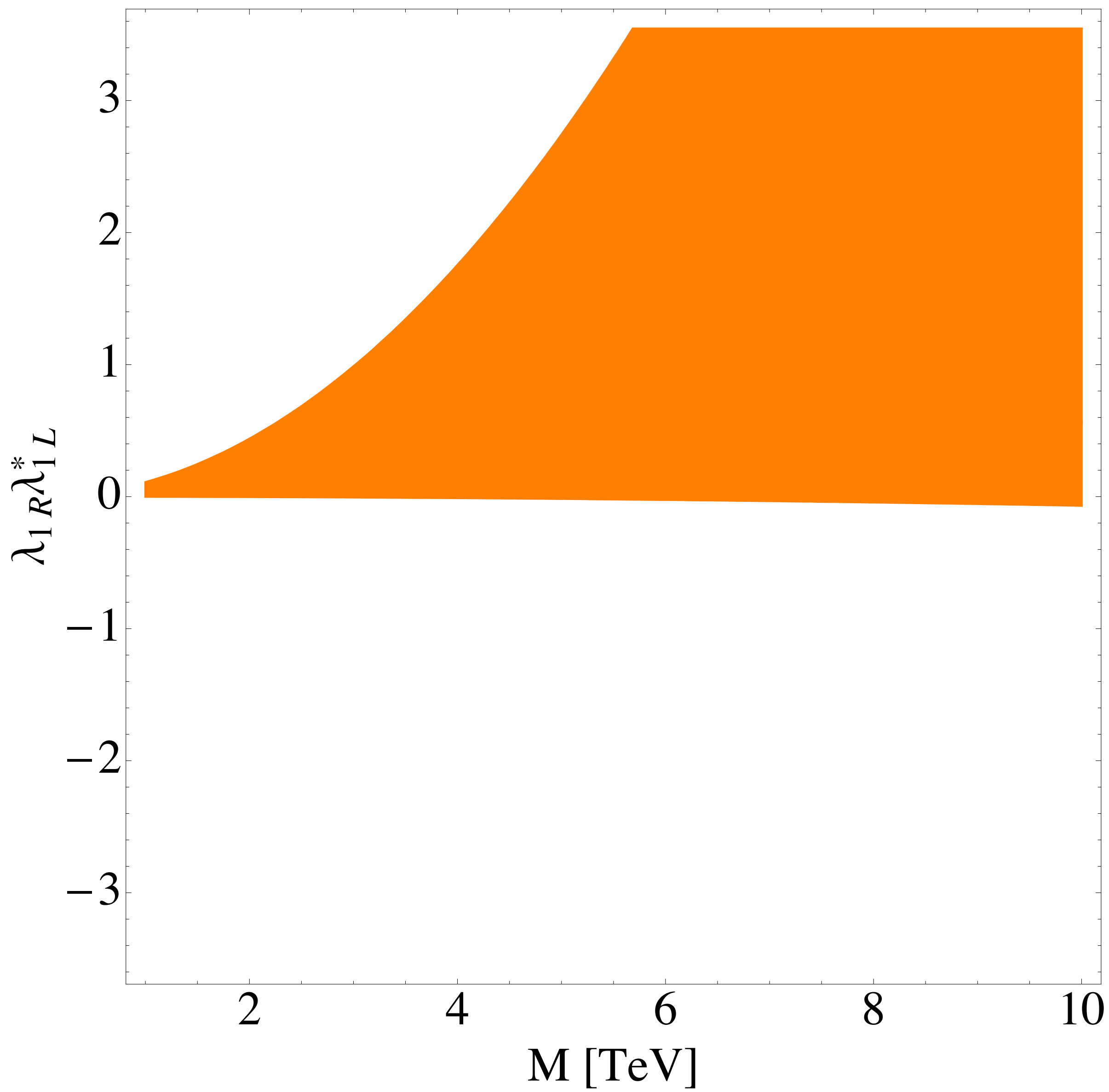
The $S_1 + S_3$ lepto-quark model for example: Gherardi et al, 2003.12525 (JHEP)

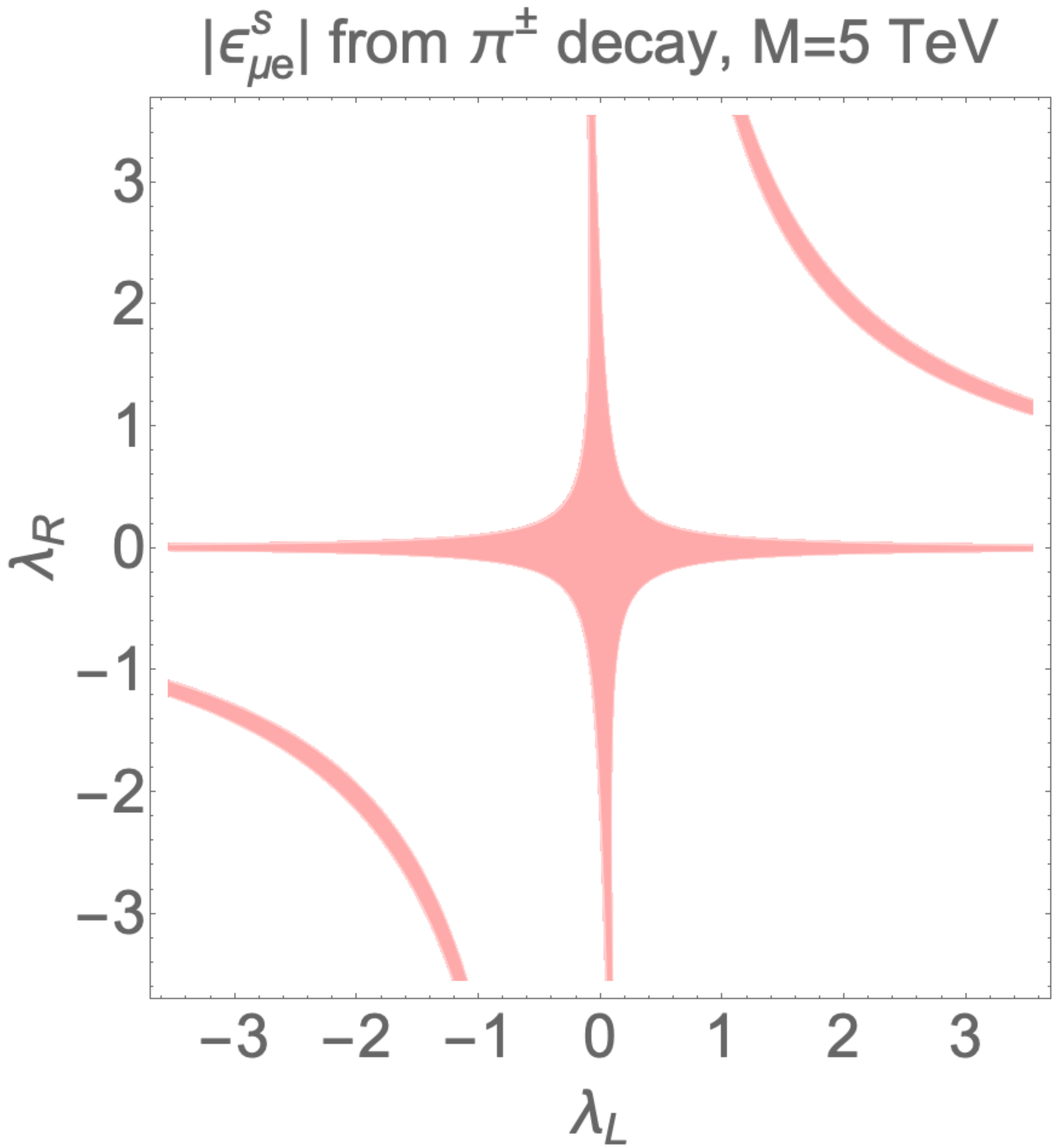
$$C^{(1)}_{lequ,prst} = \frac{\lambda^{1R}_{tr}\lambda^{1L*}_{sp}}{2M_1^2}, \qquad C^{(3)}_{lequ,prst} = -\frac{\lambda^{1R}_{tr}\lambda^{1L*}_{sp}}{8M_1^2}$$



Results

Synergy with other experiments, neutrino oscillations for example?





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

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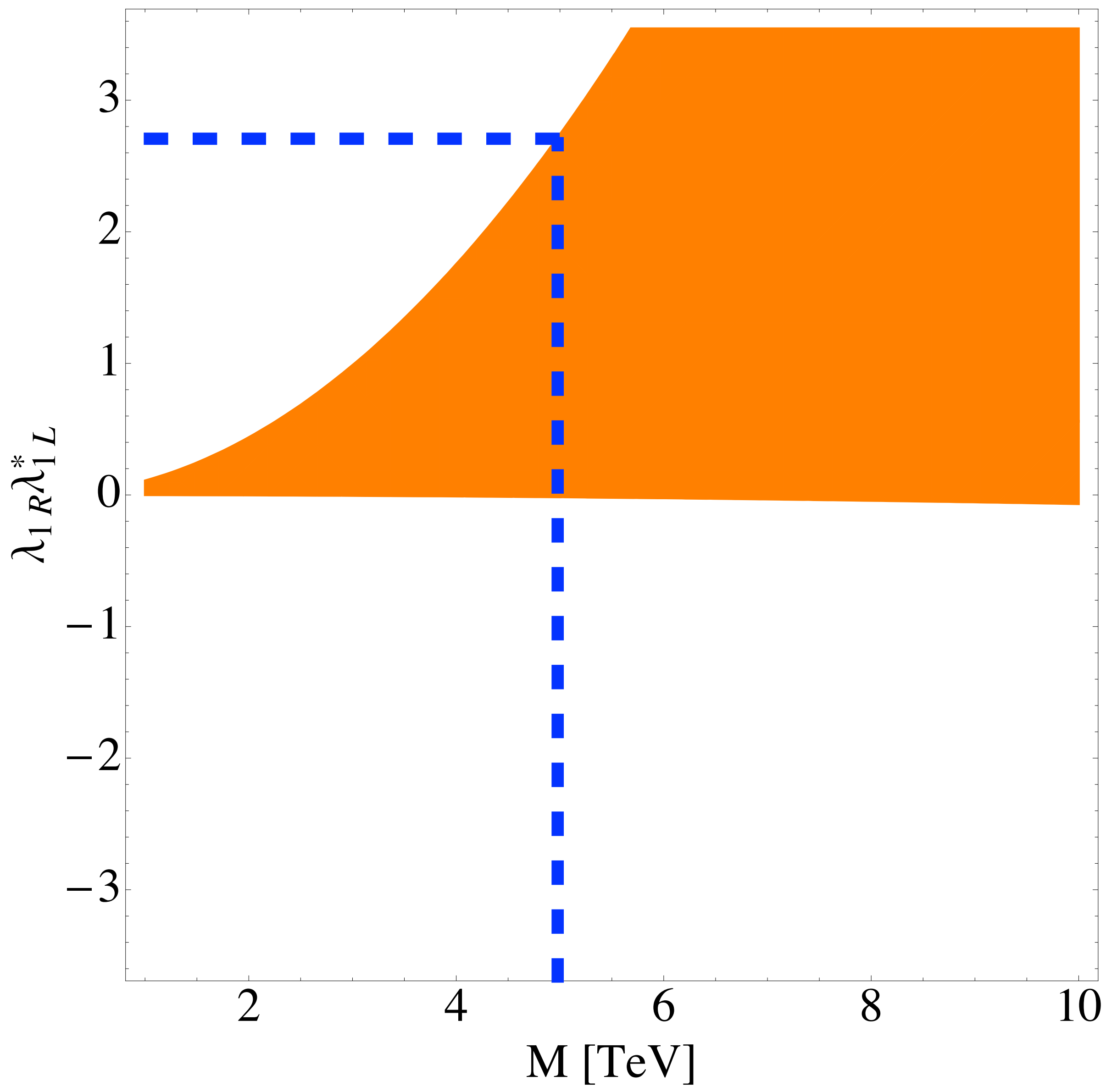
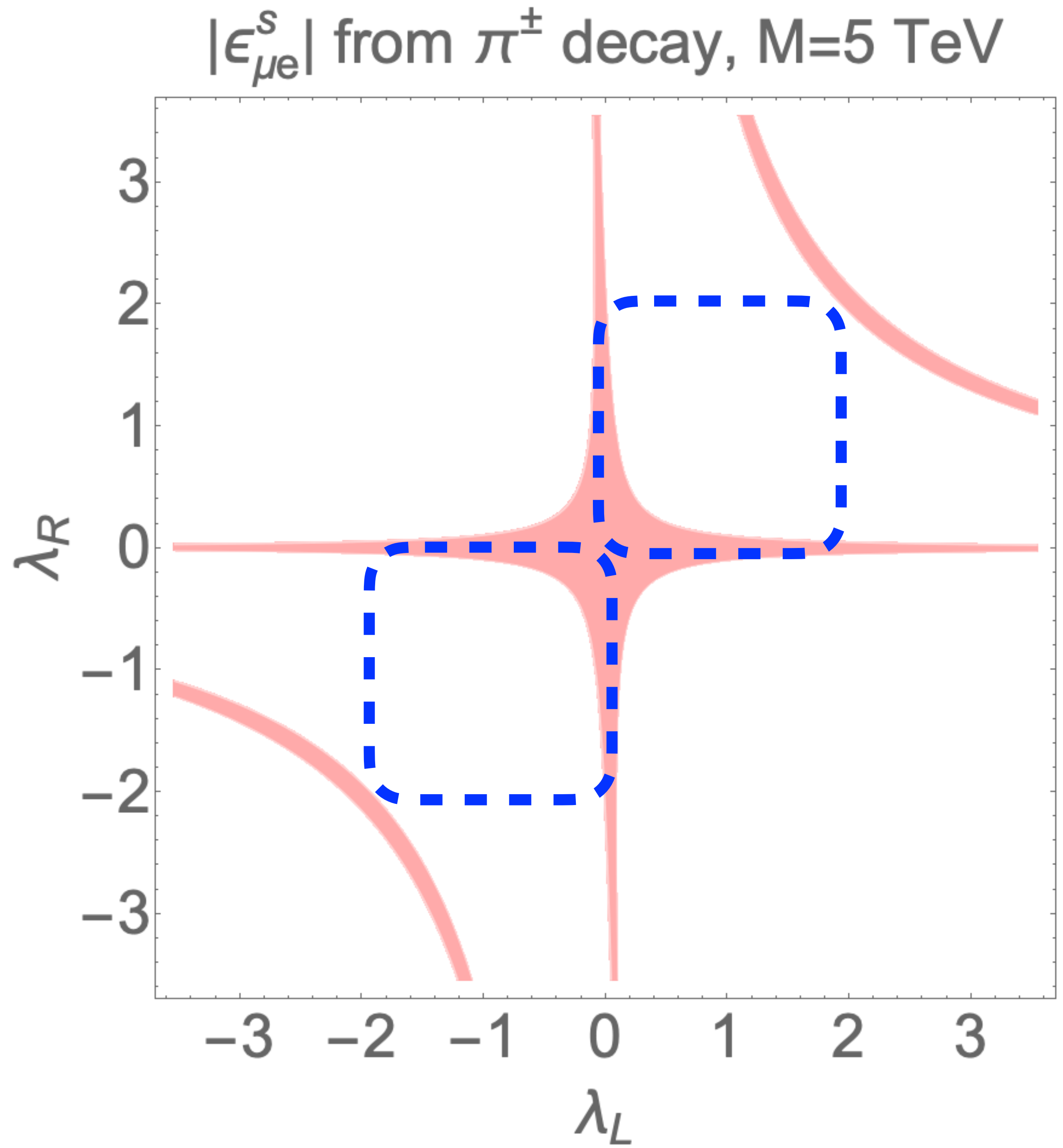
Synergy with other experiments, neutrino oscillations for example?



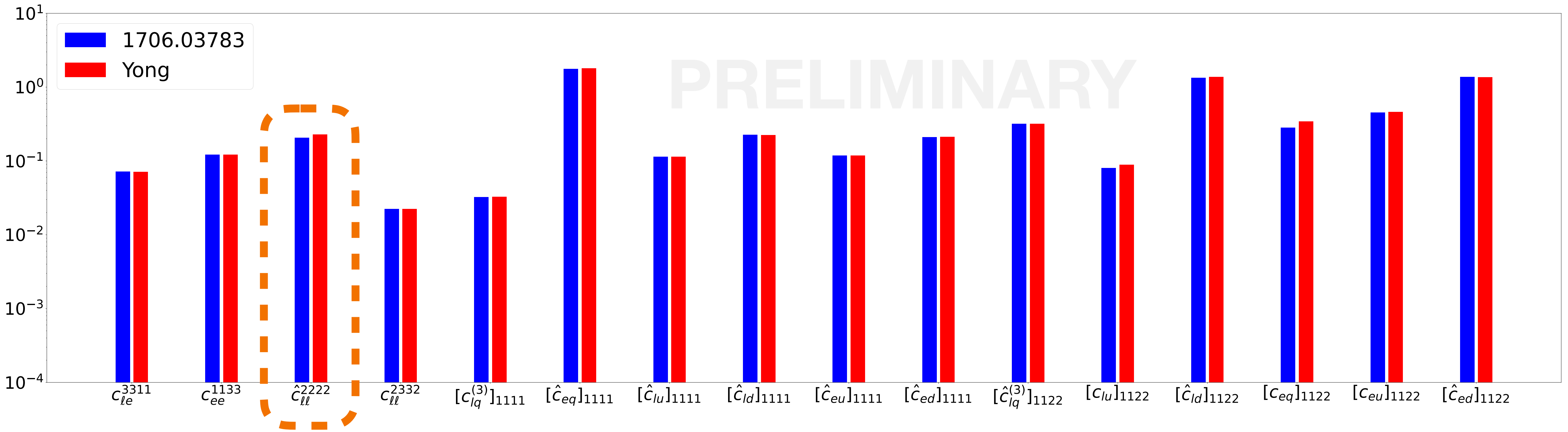


YD, Li, Jian, Vihonen, Yu, 2011.14292 (JHEP)

Results

On-going with de Blas, Grojean, Gu, Miralles, Peskin, Tian, Vos, Vryonidou

Looking forward?



$$\left[\hat{c}_{\ell\ell}\right]_{2222} = \left[c_{\ell\ell}\right]_{2222} + \frac{2g_Y^2}{g_L^2 + 3g_Y^2}\left[c_{\ell e}\right]_{2222}$$

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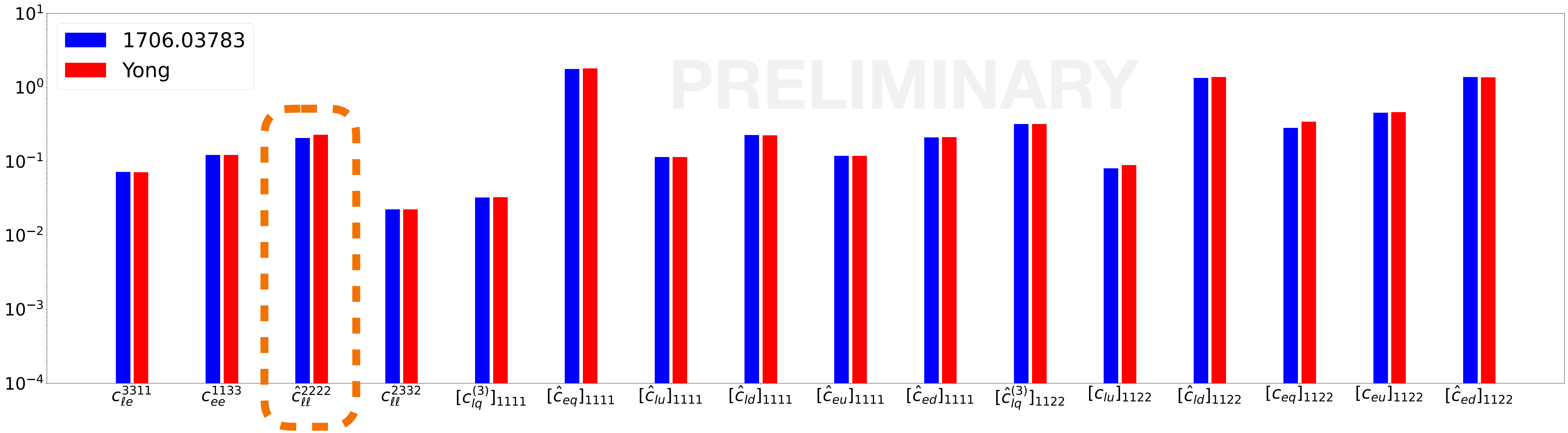

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1) Trident production (μ flavor) at FASERν to lift the flat direction?

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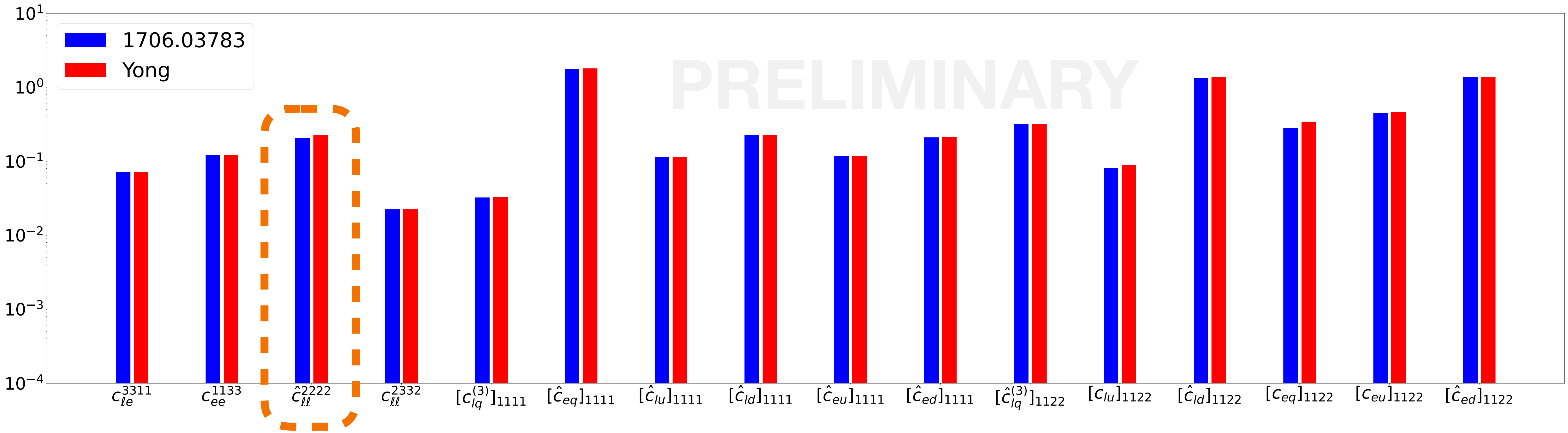

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2) Currently, no sensitivity to $\mathcal{O}_{\ell\ell,\ell e,ee}$ operators in the 3rd generation. Given its high energy/luminosity, neutrino trident production (τ flavor) at FASERν?

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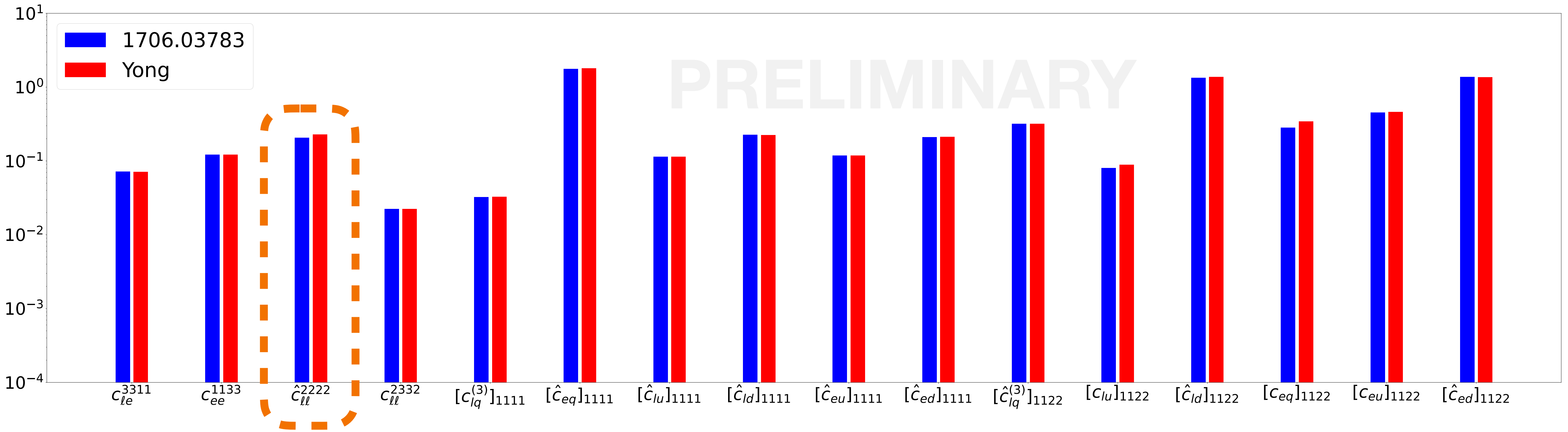

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3) Constraints on $\mathcal{O}_{\ell\ell qq,33st}$?

4) …

Summary

- We briefly review 4-fermion operators and their connection with various experiments (PVES, CKM unitarity…)
- We investigate what FASERν can add to the big picture of 4-fermion operators
  - Model independently, we obtain constraints on SMEFT operators
  - These constraints can then be easily translated to specific UV models. We use the leptoquark model to illustrate synergy of FASERν in model testing.
- We propose some future directions for the study of FASERν (on τ physics and global fit), which are still under study.

Literally the first day of the Year of the Tiger. Happy Chinese New Year and my best wishes!