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Global LFV constraints on EFTs

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arXiv: 2403.09772

*with **Enrique Fernández-Martínez** and **Daniel Naredo-Tuero***

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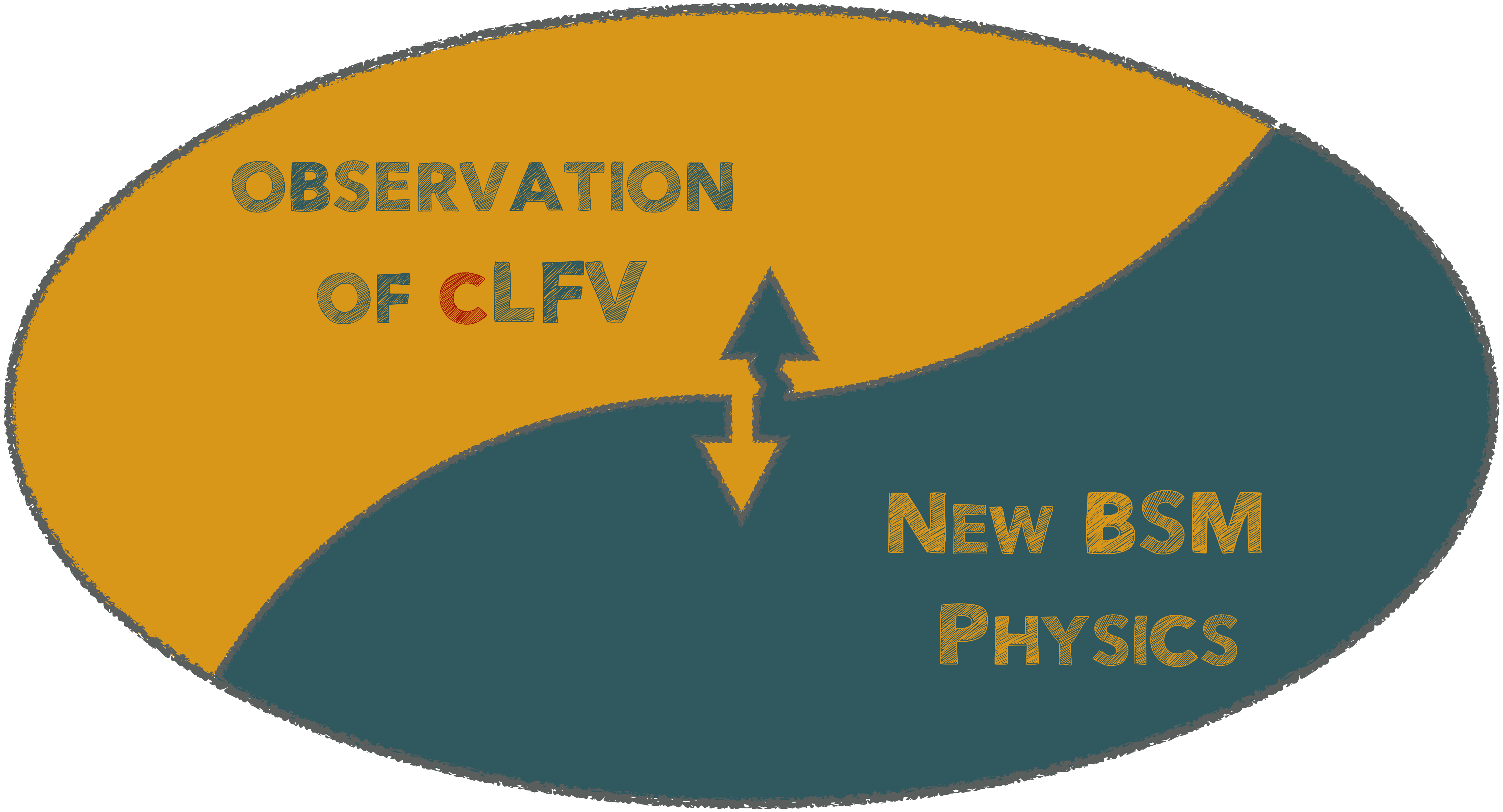
PheNumenal

EXCELENCIA SEVERO OCHOA

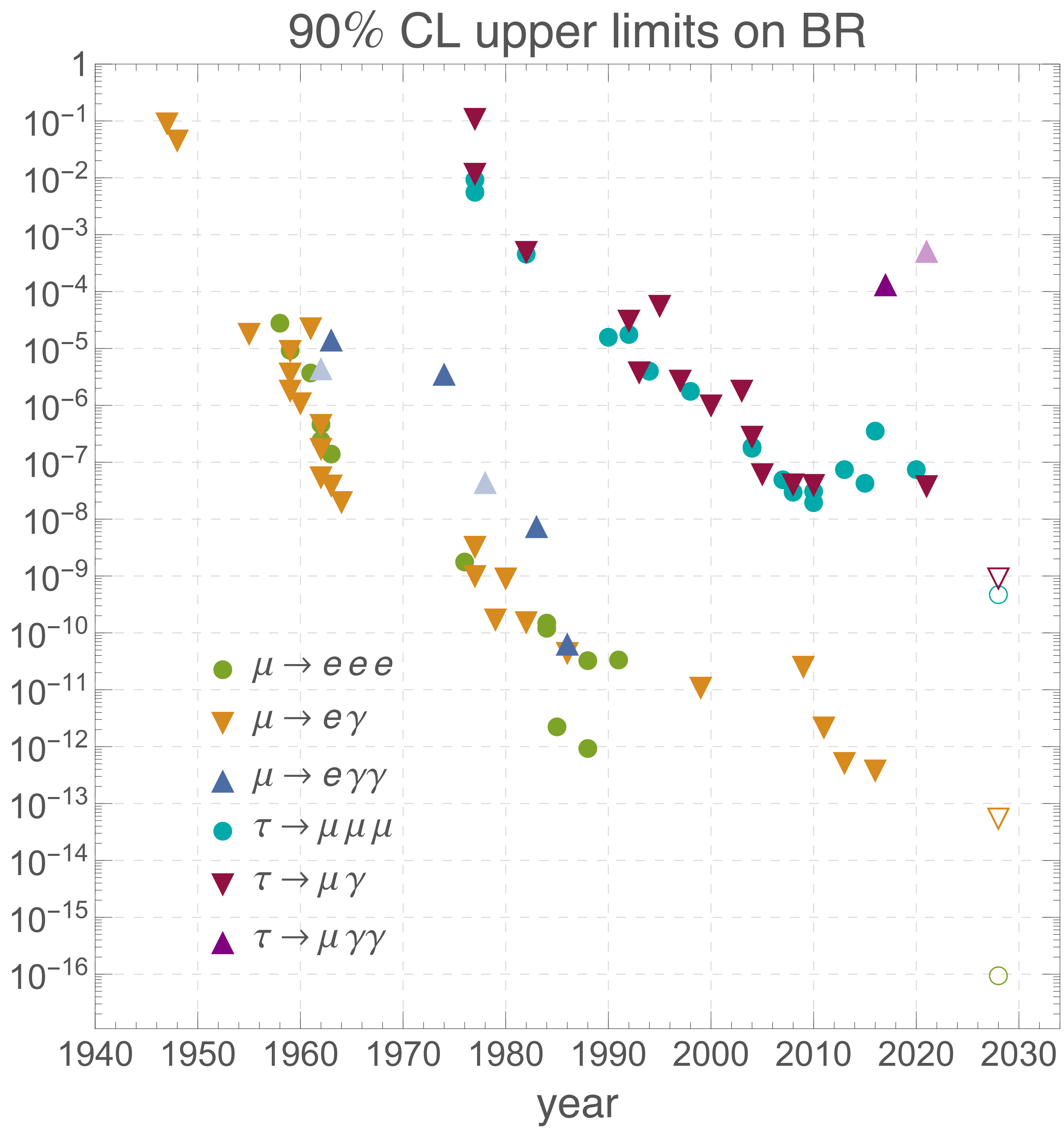
WHY LEPTON FLAVOR VIOLATION?

— *Talk by Sacha Davidson on Friday*—

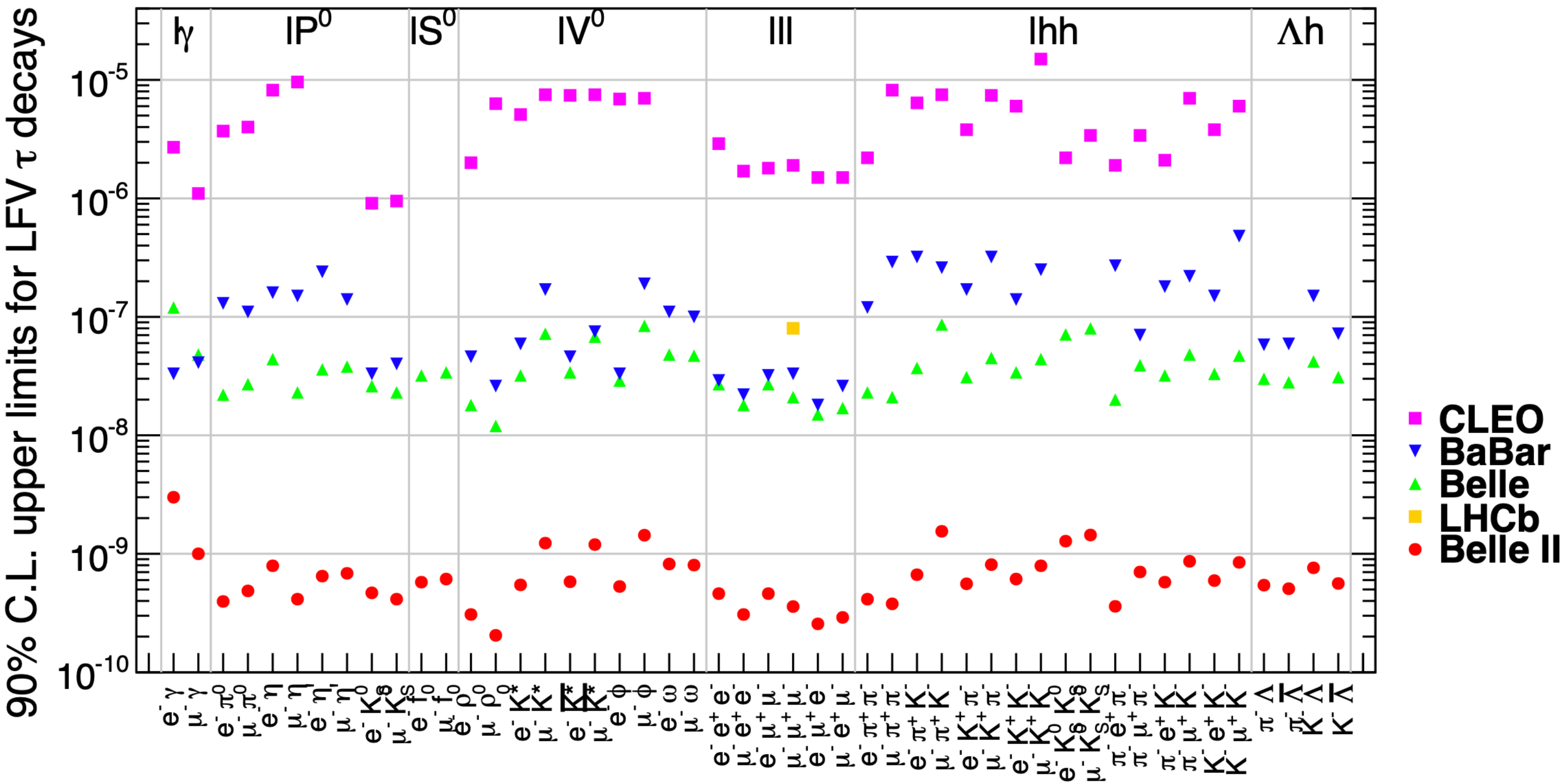


Long story

— *Fortuna, Ibarra, XM, Marín, Roig [2210.05703]* —



Belle II Physics Book — 1808.10567



— EFT APPROACH —

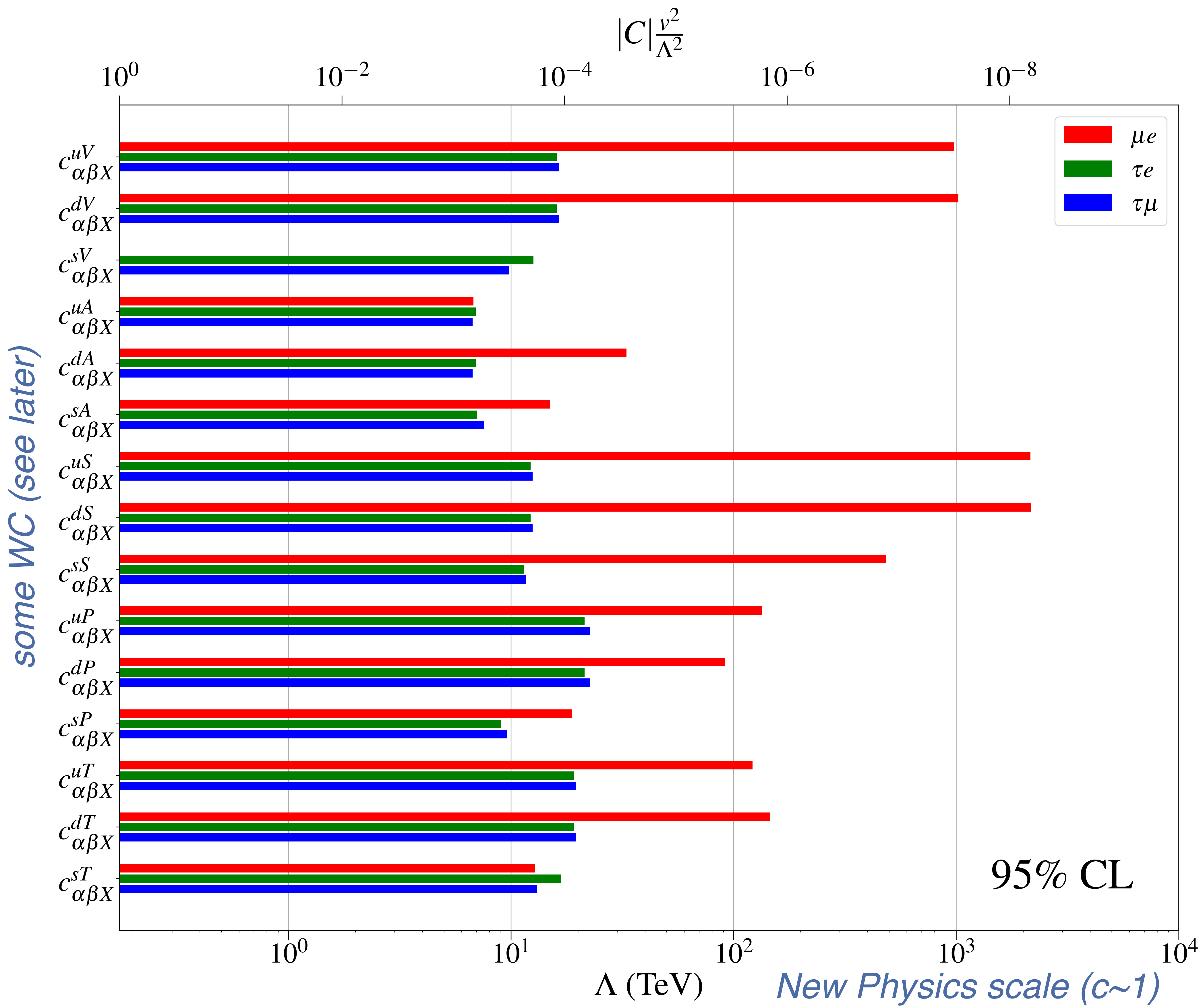
- *Motivation I: lack of new light physics* $\Longrightarrow \Lambda \gg m_W$

- *Motivation II: model-independent analysis*

— bottom-up approach—

— Many works: Raidal'97, Kuno'22, Brignole '04, Cirigliano'09, Crivellin '13, Celis'14, Crivellin'17, Cirigliano '17, Davidson'17,Falkowski '21, Cirigliano '21, Calibbi'21, Davidson'22, Calibbi'22, Plakias'23… —

First look at the EFT status



First look at the EFT status

What do we really know about the EFT framework?

cLFV Physics well constrained

$$\Lambda > 10 - 1000 \text{ TeV}$$

First look at the EFT status

What do we really REALLY know about the EFT framework?

cLFV Physics well constrained

$$\Lambda > 10 - 1000 \text{ TeV}$$

— We need a Global Picture —

arXiv: 2403.09772

Global Lepton Flavour Violating Constraints on New Physics

*Enrique Fernández-Martínez, XM and **Daniel Naredo-Tuero***

— See also previous partial analyses: Husek '20, Davidson'22, Banerjee '22, Hoferichter'23 —

— Looking for the Global Picture —

- *EFT framework(s)*

  — which one(s)?—

- *Technical details*

  — very few, ask me for more!—

- *Results*

— Looking for the Global Picture —

- *EFT framework(s)*

  — which one(s)?—

- *Technical details*

  — very few, ask me for more!—

- *Results*

	$e\mu$	$\tau\ell$
Fully Leptonic		
Semileptonic		

— Looking for the Global Picture —

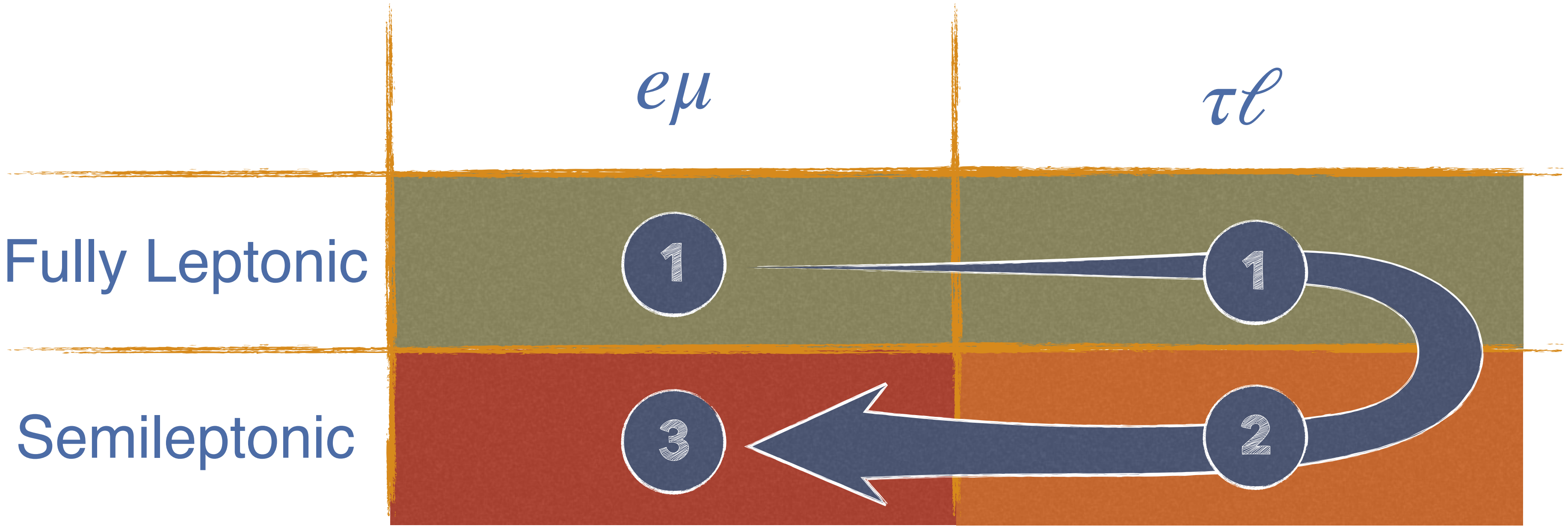
- *EFT framework(s)*

  — which one(s)?—

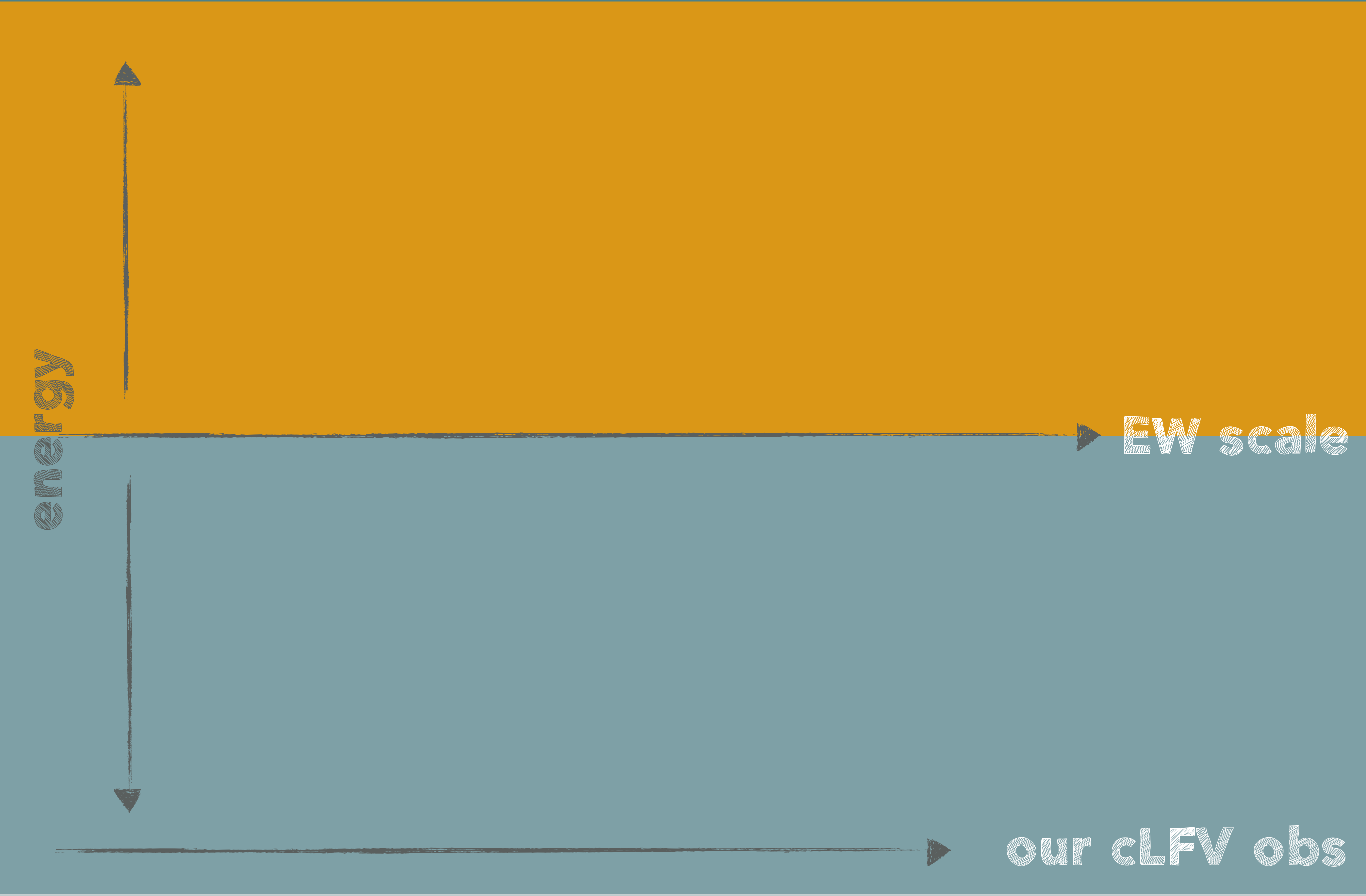
- *Technical details*

  — very few, ask me for more!—

- *Results*



Low and High Energy EFTs



Low and High Energy EFTs

energy

SMEFT

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda} \sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2} \sum_a C_a^{(6)} Q_a^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

new physics above the EW scale

EW scale

our cLFV obs

Low and High Energy EFTs

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\mathscr{L}_{\rm SMEFT} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

energy

SMEFT

cale

our cLFV obs

Warsaw basis [1008.4884]

2q2ℓ operators			
$\mathcal{O}^{(1)}_{\ell q,\alpha\beta\gamma\delta}$	$(\bar L_\alpha \gamma_\mu L_\beta)(\bar Q_\gamma \gamma^\mu Q_\delta)$	$\mathcal{O}^{(3)}_{\ell q,\alpha\beta\gamma\delta}$	$(\bar L_\alpha \gamma_\mu \tau^I L_\beta)(\bar Q_\gamma \gamma^\mu \tau^I Q_\delta)$
$\mathcal{O}_{\ell u,\alpha\beta\gamma\delta}$	$(\bar L_\alpha \gamma_\mu L_\beta)(\bar u_\gamma \gamma^\mu u_\delta)$	$\mathcal{O}_{\ell d,\alpha\beta\gamma\delta}$	$(\bar L_\alpha \gamma_\mu L_\beta)(\bar d_\gamma \gamma^\mu d_\delta)$
$\mathcal{O}_{eu,\alpha\beta\gamma\delta}$	$(\bar e_\alpha \gamma_\mu e_\beta)(\bar u_\gamma \gamma^\mu u_\delta)$	$\mathcal{O}_{ed,\alpha\beta\gamma\delta}$	$(\bar e_\alpha \gamma_\mu e_\beta)(\bar d_\gamma \gamma^\mu d_\delta)$
$\mathcal{O}_{qe,\alpha\beta\gamma\delta}$	$(\bar Q_\alpha \gamma^\mu Q_\beta)(\bar e_\gamma \gamma_\mu e_\delta)$	$\mathcal{O}_{\ell edq,\alpha\beta\gamma\delta}$	$(\bar L_\alpha e_\beta)(\bar d_\gamma Q_\delta)$
$\mathcal{O}^{(1)}_{\ell equ,\alpha\beta\gamma\delta}$	$(\bar L^a_\alpha e_\beta)\epsilon_{ab}(\bar Q^b_\gamma u_\delta)$	$\mathcal{O}^{(3)}_{\ell equ,\alpha\beta\gamma\delta}$	$(\bar L^a_\alpha \sigma_{\mu\nu} e_\beta)\epsilon_{ab}(\bar Q^b_\gamma \sigma^{\mu\nu} u_\delta)$
4ℓ operators		**Dipole operators**	
$\mathcal{O}_{\ell\ell,\alpha\beta\gamma\delta}$	$(\bar L_\alpha \gamma_\mu L_\beta)(\bar L_\gamma \gamma^\mu L_\delta)$	$\mathcal{O}_{eW,\alpha\beta}$	$(\bar L_\alpha \sigma^{\mu\nu} e_\beta)\tau^I H W^I_{\mu\nu}$
$\mathcal{O}_{ee,\alpha\beta\gamma\delta}$	$(\bar e_\alpha \gamma_\mu e_\beta)(\bar e_\gamma \gamma^\mu e_\delta)$	$\mathcal{O}_{eB,\alpha\beta}$	$(\bar L_\alpha \sigma^{\mu\nu} e_\beta) H B_{\mu\nu}$
$\mathcal{O}_{\ell e,\alpha\beta\gamma\delta}$	$(\bar L_\alpha \gamma_\mu L_\beta)(\bar e_\gamma \gamma^\mu e_\delta)$		
Lepton-Higgs operators			
$\mathcal{O}^{(1)}_{H\ell,\alpha\beta}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar L_\alpha \gamma^\mu L_\beta)$	$\mathcal{O}^{(3)}_{H\ell,\alpha\beta}$	$(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar L_\alpha \gamma^\mu \tau^I L_\beta)$
$\mathcal{O}_{He,\alpha\beta}$	$(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar e_\alpha \gamma^\mu e_\beta)$	$\mathcal{O}_{eH,\alpha\beta}$	$(\bar L_\alpha e_\beta H)(H^\dagger H)$

Low and High Energy EFTs

energy

SMEFT

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

cLFV at dim-6

EW scale

LEFT

$$SU(3)_c \times U(1)_{EM}$$

$$\mathcal{L}_{\rm LEFT}^{\rm dim-5} \supset \frac{\sqrt{2}}{v}\sum_{\alpha\neq\beta} c_{\alpha\beta}^{e\gamma} (\bar{e}_{L_\alpha}\sigma^{\mu\nu} e_{R_\beta})F_{\mu\nu} + hc$$

$$\mathcal{L}_{\rm LEFT}^{\rm dim-6} \supset \frac{2}{v^2}\sum_{q,x,Y} c_{\alpha\beta X}^{qx}\, \mathcal{O}_{\alpha\beta X}^{qx} + \frac{2}{v^2}\sum_{y,X,Y} c_{\alpha\beta X}^{\gamma\delta Y y}\, \mathcal{O}_{\alpha\beta X}^{\gamma\delta Y y}$$

our cLFV obs

Low and High Energy EFTs

Adapted from Jenkins et al [1709.04486]

Leptonic	
$\mathcal{O}^{\gamma\delta LV}_{\alpha\beta L}$	$(\bar e_{L\alpha}\gamma^\mu e_{L\beta})(\bar e_{L\gamma}\gamma_\mu e_{L\delta})$
$\mathcal{O}^{\gamma\delta RV}_{\alpha\beta R}$	$(\bar e_{R\alpha}\gamma^\mu e_{R\beta})(\bar e_{R\gamma}\gamma_\mu e_{R\delta})$
$\mathcal{O}^{\gamma\delta RV}_{\alpha\beta L}$	$(\bar e_{L\alpha}\gamma^\mu e_{L\beta})(\bar e_{R\gamma}\gamma_\mu e_{R\delta})$
$\mathcal{O}^{\gamma\delta LV}_{\alpha\beta R}$	$(\bar e_{R\alpha}\gamma^\mu e_{R\beta})(\bar e_{L\gamma}\gamma_\mu e_{L\delta})$
$\mathcal{O}^{\gamma\delta RS}_{\alpha\beta R}$	$(\bar e_{L\alpha}e_{R\beta})(\bar e_{L\gamma}e_{R\delta})+\text{h.c.}$

Dipole	
$\mathcal{O}^{e\gamma}_{\alpha\beta}$	$(\bar e_{L\alpha}\sigma^{\mu\nu}e_{R\beta})F_{\mu\nu}+\text{h.c.}$

up − quarks	
$\mathcal{O}^{uV}_{\alpha\beta L}$	$(\bar u\gamma_\mu u)(\bar e_{L\alpha}\gamma^\mu e_{L\beta})$
$\mathcal{O}^{uA}_{\alpha\beta L}$	$(\bar u\gamma_\mu\gamma_5 u)(\bar e_{L\alpha}\gamma^\mu e_{L\beta})$
$\mathcal{O}^{uV}_{\alpha\beta R}$	$(\bar u\gamma_\mu u)(\bar e_{R\alpha}\gamma^\mu e_{R\beta})$
$\mathcal{O}^{uA}_{\alpha\beta R}$	$(\bar u\gamma_\mu\gamma_5 u)(\bar e_{R\alpha}\gamma^\mu e_{R\beta})$
$\mathcal{O}^{uS}_{\alpha\beta R}$	$(\bar u u)(\bar e_{L\alpha}e_{R\beta})+\text{h.c.}$
$\mathcal{O}^{uP}_{\alpha\beta R}$	$(\bar u\gamma_5 u)(\bar e_{L\alpha}e_{R\beta})+\text{h.c.}$
$\mathcal{O}^{uT}_{\alpha\beta R}$	$(\bar u\sigma_{\mu\nu}u)(\bar e_{L\alpha}\sigma^{\mu\nu}e_{R\beta})+\text{h.c.}$

down − quarks	
$\mathcal{O}^{dV}_{\alpha\beta L}$	$(\bar d\gamma_\mu d)(\bar e_{L\alpha}\gamma^\mu e_{L\beta})$
$\mathcal{O}^{dA}_{\alpha\beta L}$	$(\bar d\gamma_\mu\gamma_5 d)(\bar e_{L\alpha}\gamma^\mu e_{L\beta})$
$\mathcal{O}^{dV}_{\alpha\beta R}$	$(\bar d\gamma_\mu d)(\bar e_{R\alpha}\gamma^\mu e_{R\beta})$
$\mathcal{O}^{dA}_{\alpha\beta R}$	$(\bar d\gamma_\mu\gamma_5 d)(\bar e_{R\alpha}\gamma^\mu e_{R\beta})$
$\mathcal{O}^{dS}_{\alpha\beta R}$	$(\bar d d)(\bar e_{L\alpha}e_{R\beta})+\text{h.c.}$
$\mathcal{O}^{dP}_{\alpha\beta R}$	$(\bar d\gamma_5 d)(\bar e_{L\alpha}e_{R\beta})+\text{h.c.}$
$\mathcal{O}^{dT}_{\alpha\beta R}$	$(\bar d\sigma_{\mu\nu}d)(\bar e_{L\alpha}\sigma^{\mu\nu}e_{R\beta})+\text{h.c.}$

energy

EW scale

$SU(3)_c \times U(1)_{EM}$

LEFT

$$\mathcal{L}^{\rm dim-5}_{\rm LEFT} \supset \frac{\sqrt{2}}{v}\sum_{\alpha\neq\beta} c^{e\gamma}_{\alpha\beta}(\bar e_{L_\alpha}\sigma^{\mu\nu}e_{R_\beta})F_{\mu\nu} + hc$$

← dipole

$$\mathcal{L}^{\rm dim-6}_{\rm LEFT} \supset \frac{2}{v^2}\sum_{q,x,Y} c^{qx}_{\alpha\beta X}\,\mathcal{O}^{qx}_{\alpha\beta X} + \frac{2}{v^2}\sum_{y,X,Y} c^{\gamma\delta Yy}_{\alpha\beta X}\,\mathcal{O}^{\gamma\delta Yy}_{\alpha\beta X}$$

← 4-fermion

our cLFV obs

— SMEFT or LEFT? —

— SMEFT or LEFT? —

YES

Scenarios

Leptonic	
$\mathcal{O}^{\gamma\delta LV}_{\alpha\beta L}$	$(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})(\bar{e}_{L\gamma}\gamma_\mu e_{L\delta})$
$\mathcal{O}^{\gamma\delta RV}_{\alpha\beta R}$	$(\bar{e}_{R\alpha}\gamma^\mu e_{R\beta})(\bar{e}_{R\gamma}\gamma_\mu e_{R\delta})$
$\mathcal{O}^{\gamma\delta RV}_{\alpha\beta L}$	$(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})(\bar{e}_{R\gamma}\gamma_\mu e_{R\delta})$
$\mathcal{O}^{\gamma\delta LV}_{\alpha\beta R}$	$(\bar{e}_{R\alpha}\gamma^\mu e_{R\beta})(\bar{e}_{L\gamma}\gamma_\mu e_{L\delta})$
$\mathcal{O}^{\gamma\delta RS}_{\alpha\beta R}$	$(\bar{e}_{L\alpha} e_{R\beta})(\bar{e}_{L\gamma} e_{R\delta}) + \text{h.c.}$

Dipole	
$\mathcal{O}^{e\gamma}_{\alpha\beta}$	$(\bar{e}_{L\alpha}\sigma^{\mu\nu} e_{R\beta})F_{\mu\nu} + \text{h.c.}$

up − quarks		down − quarks	
$\mathcal{O}^{uV}_{\alpha\beta L}$	$(\bar{u}\gamma_\mu u)(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})$	$\mathcal{O}^{dV}_{\alpha\beta L}$	$(\bar{d}\gamma_\mu d)(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})$
$\mathcal{O}^{uA}_{\alpha\beta L}$	$(\bar{u}\gamma_\mu\gamma_5 u)(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})$	$\mathcal{O}^{dA}_{\alpha\beta L}$	$(\bar{d}\gamma_\mu\gamma_5 d)(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})$
$\mathcal{O}^{uV}_{\alpha\beta R}$	$(\bar{u}\gamma_\mu u)(\bar{e}_{R\alpha}\gamma^\mu e_{R\beta})$	$\mathcal{O}^{dV}_{\alpha\beta R}$	$(\bar{d}\gamma_\mu d)(\bar{e}_{R\alpha}\gamma^\mu e_{R\beta})$
$\mathcal{O}^{uA}_{\alpha\beta R}$	$(\bar{u}\gamma_\mu\gamma_5 u)(\bar{e}_{R\alpha}\gamma^\mu e_{R\beta})$	$\mathcal{O}^{dA}_{\alpha\beta R}$	$(\bar{d}\gamma_\mu\gamma_5 d)(\bar{e}_{R\alpha}\gamma^\mu e_{R\beta})$
$\mathcal{O}^{uS}_{\alpha\beta R}$	$(\bar{u}u)(\bar{e}_{L\alpha} e_{R\beta}) + \text{h.c.}$	$\mathcal{O}^{dS}_{\alpha\beta R}$	$(\bar{d}d)(\bar{e}_{L\alpha} e_{R\beta}) + \text{h.c.}$
$\mathcal{O}^{uP}_{\alpha\beta R}$	$(\bar{u}\gamma_5 u)(\bar{e}_{L\alpha} e_{R\beta}) + \text{h.c.}$	$\mathcal{O}^{dP}_{\alpha\beta R}$	$(\bar{d}\gamma_5 d)(\bar{e}_{L\alpha} e_{R\beta}) + \text{h.c.}$
$\mathcal{O}^{uT}_{\alpha\beta R}$	$(\bar{u}\sigma_{\mu\nu} u)(\bar{e}_{L\alpha}\sigma^{\mu\nu} e_{R\beta}) + \text{h.c.}$	$\mathcal{O}^{dT}_{\alpha\beta R}$	$(\bar{d}\sigma_{\mu\nu} d)(\bar{e}_{L\alpha}\sigma^{\mu\nu} e_{R\beta}) + \text{h.c.}$

— LEFT —

All operators are independent

Scenarios

Leptonic		up − quarks		down − quarks	
$\mathcal{O}^{\gamma\delta LV}_{\alpha\beta L}$	$(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})(\bar{e}_{L\gamma}\gamma_{\mu}e_{L\delta})$	$\mathcal{O}^{uV}_{\alpha\beta L}$	$(\bar{u}\gamma_{\mu}u)(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})$	$\mathcal{O}^{dV}_{\alpha\beta L}$	$(\bar{d}\gamma_{\mu}d)(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})$
$\mathcal{O}^{\gamma\delta RV}_{\alpha\beta R}$	$(\bar{e}_{R\alpha}\gamma^{\mu}e_{R\beta})(\bar{e}_{R\gamma}\gamma_{\mu}e_{R\delta})$	$\mathcal{O}^{uA}_{\alpha\beta L}$	$(\bar{u}\gamma_{\mu}\gamma_5 u)(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})$	$\mathcal{O}^{dA}_{\alpha\beta L}$	$(\bar{d}\gamma_{\mu}\gamma_5 d)(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})$
$\mathcal{O}^{\gamma\delta RV}_{\alpha\beta L}$	$(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})(\bar{e}_{R\gamma}\gamma_{\mu}e_{R\delta})$	$\mathcal{O}^{uV}_{\alpha\beta R}$	$(\bar{u}\gamma_{\mu}u)(\bar{e}_{R\alpha}\gamma^{\mu}e_{R\beta})$	$\mathcal{O}^{dV}_{\alpha\beta R}$	$(\bar{d}\gamma_{\mu}d)(\bar{e}_{R\alpha}\gamma^{\mu}e_{R\beta})$
$\mathcal{O}^{\gamma\delta LV}_{\alpha\beta R}$	$(\bar{e}_{R\alpha}\gamma^{\mu}e_{R\beta})(\bar{e}_{L\gamma}\gamma_{\mu}e_{L\delta})$	$\mathcal{O}^{uA}_{\alpha\beta R}$	$(\bar{u}\gamma_{\mu}\gamma_5 u)(\bar{e}_{R\alpha}\gamma^{\mu}e_{R\beta})$	$\mathcal{O}^{dA}_{\alpha\beta R}$	$(\bar{d}\gamma_{\mu}\gamma_5 d)(\bar{e}_{R\alpha}\gamma^{\mu}e_{R\beta})$
$\mathcal{O}^{\gamma\delta RS}_{\alpha\beta R}$	$(\bar{e}_{L\alpha}e_{R\beta})(\bar{e}_{L\gamma}e_{R\delta})$ + h.c.	$\mathcal{O}^{uS}_{\alpha\beta R}$	$(\bar{u}u)(\bar{e}_{L\alpha}e_{R\beta})$ + h.c.	$\mathcal{O}^{dS}_{\alpha\beta R}$	$(\bar{d}d)(\bar{e}_{L\alpha}e_{R\beta})$ + h.c.
Dipole		$\mathcal{O}^{uP}_{\alpha\beta R}$	$(\bar{u}\gamma_5 u)(\bar{e}_{L\alpha}e_{R\beta})$ + h.c.	$\mathcal{O}^{dP}_{\alpha\beta R}$	$(\bar{d}\gamma_5 d)(\bar{e}_{L\alpha}e_{R\beta})$ + h.c.
$\mathcal{O}^{e\gamma}_{\alpha\beta}$	$(\bar{e}_{L\alpha}\sigma^{\mu\nu}e_{R\beta})F_{\mu\nu}$ + h.c.	$\mathcal{O}_{\alpha\beta R}$	$(\bar{u}\sigma_{\mu\nu}u)(\bar{e}_{L\alpha}\sigma^{\mu\nu}e_{R\beta})$ + h.c.	$\mathcal{O}_{\alpha\beta R}$	$(\bar{d}\sigma_{\mu\nu}d)(\bar{e}_{L\alpha}\sigma^{\mu\nu}e_{R\beta})$ + h.c.

less freedom

— LEFT —

All operators are independent

— SMEFT (3flavor) —

SMEFT induced relations. Only light quarks u,d,s

Scenarios

Leptonic	
$\mathcal{O}^{\gamma\delta LV}_{\alpha\beta L}$	$(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})(\bar{e}_{L\gamma}\gamma_{\mu}e_{L\delta})$
$\mathcal{O}^{\gamma\delta RV}_{\alpha\beta R}$	$(\bar{e}_{R\alpha}\gamma^{\mu}e_{R\beta})(\bar{e}_{R\gamma}\gamma_{\mu}e_{R\delta})$
$\mathcal{O}^{\gamma\delta RV}_{\alpha\beta L}$	$(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})(\bar{e}_{R\gamma}\gamma_{\mu}e_{R\delta})$
$\mathcal{O}^{\gamma\delta LV}_{\alpha\beta R}$	$(\bar{e}_{R\alpha}\gamma^{\mu}e_{R\beta})(\bar{e}_{L\gamma}\gamma_{\mu}e_{L\delta})$
$\mathcal{O}^{\gamma\delta RS}_{\alpha\beta R}$	$(\bar{e}_{L\alpha}e_{R\beta})(\bar{e}_{L\gamma}e_{R\delta}) + \text{h.c.}$
Dipole	
$\mathcal{O}^{e\gamma}_{\alpha\beta}$	$(\bar{e}_{L\alpha}\sigma^{\mu\nu}e_{R\beta})F_{\mu\nu} + \text{h.c.}$

up − quarks	
$\mathcal{O}^{uV}_{\alpha\beta L}$	$(\bar{u}\gamma_{\mu}u)(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})$
$\mathcal{O}^{uA}_{\alpha\beta L}$	$(\bar{u}\gamma_{\mu}\gamma_5 u)(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})$
$\mathcal{O}^{uV}_{\alpha\beta R}$	$(\bar{u}\gamma_{\mu}u)(\bar{e}_{R\alpha}\gamma^{\mu}e_{R\beta})$
$\mathcal{O}^{uA}_{\alpha\beta R}$	$(\bar{u}\gamma_{\mu}\gamma_5 u)(\bar{e}_{R\alpha}\gamma^{\mu}e_{R\beta})$
$\mathcal{O}^{uS}_{\alpha\beta R}$	$(\bar{u}u)(\bar{e}_{L\alpha}e_{R\beta}) + \text{h.c.}$
$\mathcal{O}^{uP}_{\alpha\beta R}$	$(\bar{u}\gamma_5 u)(\bar{e}_{L\alpha}e_{R\beta}) + \text{h.c.}$
$\mathcal{O}^{uT}_{\alpha\beta R}$	$(\bar{u}\sigma_{\mu\nu}u)(\bar{e}_{L\alpha}\sigma^{\mu\nu}e_{R\beta}) + \text{h.c.}$

down − quarks	
$\mathcal{O}^{dV}_{\alpha\beta L}$	$(\bar{d}\gamma_{\mu}d)(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})$
$\mathcal{O}^{dA}_{\alpha\beta L}$	$(\bar{d}\gamma_{\mu}\gamma_5 d)(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})$
$\mathcal{O}^{dV}_{\alpha\beta R}$	$(\bar{d}\gamma_{\mu}d)(\bar{e}_{R\alpha}\gamma^{\mu}e_{R\beta})$
$\mathcal{O}^{dA}_{\alpha\beta R}$	$(\bar{d}\gamma_{\mu}\gamma_5 d)(\bar{e}_{R\alpha}\gamma^{\mu}e_{R\beta})$
$\mathcal{O}^{dS}_{\alpha\beta R}$	$(\bar{d}d)(\bar{e}_{L\alpha}e_{R\beta}) + \text{h.c.}$
$\mathcal{O}^{dP}_{\alpha\beta R}$	$(\bar{d}\gamma_5 d)(\bar{e}_{L\alpha}e_{R\beta}) + \text{h.c.}$
$\mathcal{O}^{dT}_{\alpha\beta R}$	$(\bar{d}\sigma_{\mu\nu}d)(\bar{e}_{L\alpha}\sigma^{\mu\nu}e_{R\beta}) + \text{h.c.}$

less freedom

— LEFT —

All operators are independent

— SMEFT (3flavor) —

SMEFT induced relations. Only light quarks u,d,s

— SMEFT (2flavor) —

SMEFT induced relations. Only light quarks u,d

Technical Details

- *Only* ***quadratic contributions*** *from new physics*

— Going global is a difficult task, some simplifications as a first step —

Technical Details

- *Only **quadratic contributions** from new physics*

  — Going global is a difficult task, some simplifications as a first step —

- *Results always for low-energy WCs*

  — warning! Wilson coefficients are scale dependent $C \equiv C(\mu)$ —

- *Work at tree level*

- *WC diagonal in the quark sector and CKM = 1*

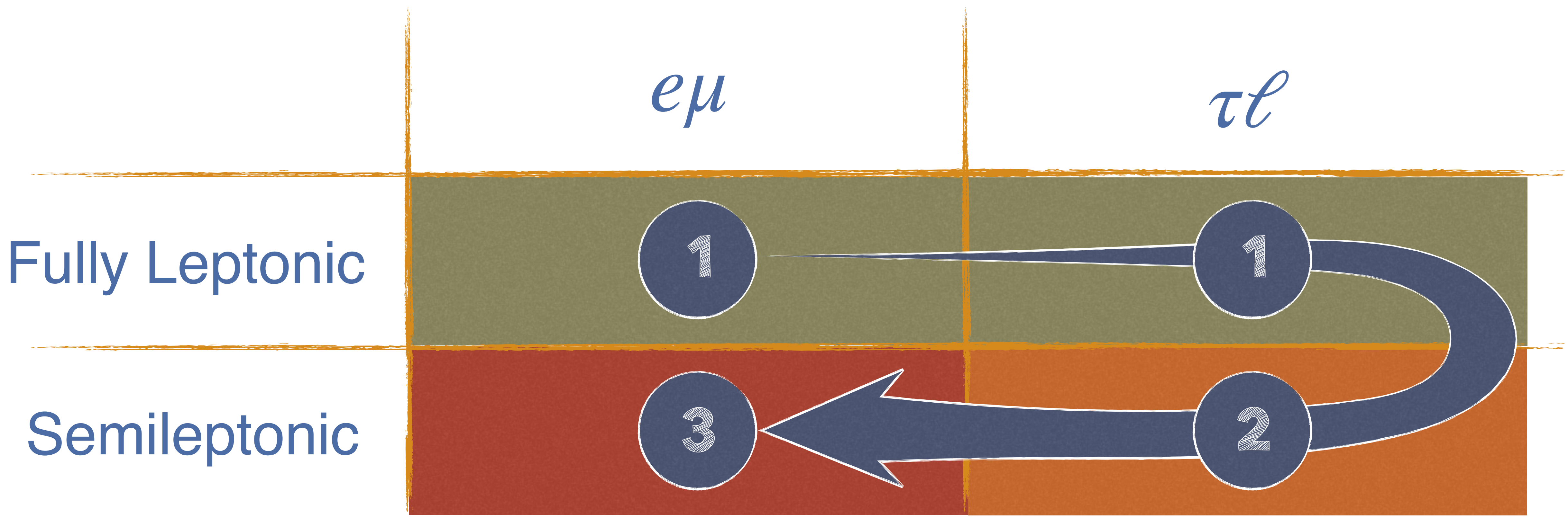
- *Operators only to light quarks*

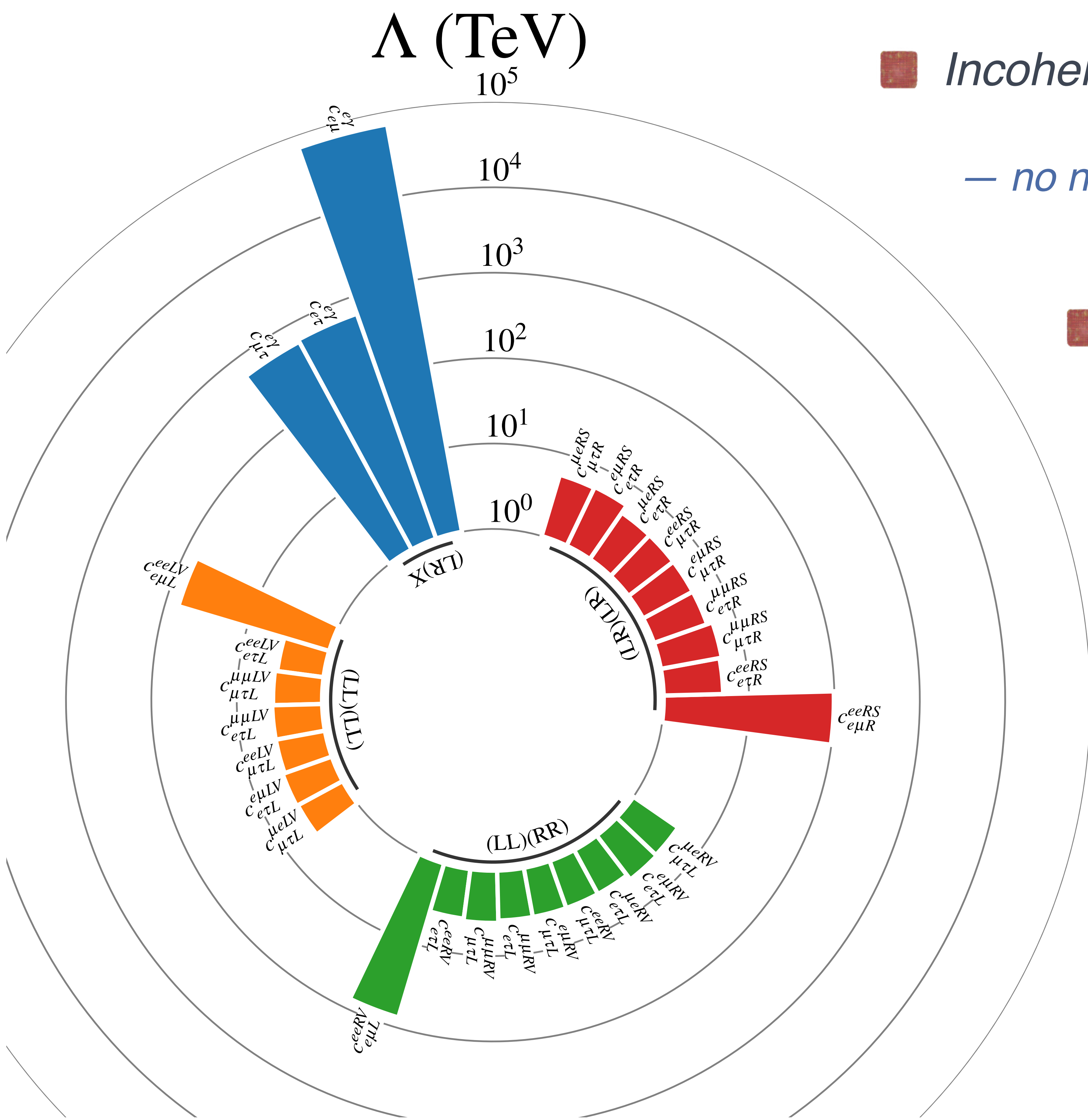
  — either (u,d,s) or only (u,d) —

- *Identify all **flat directions***

  — explore the parameter space with an adjusted MCMC—

— Global Results —





- *Incoherent contributions*

— no new inside from a global analysis —

- *Everything well constrained*

$$\Lambda \gtrsim 5 - 50000 \text{ TeV}$$

- *Few exceptions*

$$(\Delta F = 1)$$

$$\bar{e}\mu\bar{\mu}\mu,\ \bar{e}\tau\bar{\tau}\tau,\ \bar{\mu}\tau\bar{\tau}\tau,\ \bar{e}\mu\bar{\tau}\tau$$

$$(\Delta F = 2)$$

$$\bar{e}\mu\bar{e}\mu,\ \bar{e}\tau\bar{e}\tau,\ \bar{\mu}\tau\bar{\mu}\tau,\ \bar{e}\tau\bar{\mu}\tau$$

— Global Results —

	$e\mu$	$\tau\ell$
Fully Leptonic	one-at-a-time bounds = global bounds	
Semileptonic	3	2

Semileptonic Operators

- *Many mesons w/ different structures* — *great complementarity* —

$$\tau \to \ell\pi\,,\ \tau \to \ell\eta\,,\ \tau \to \ell\eta'\,,\ \tau \to \ell\omega\,,\ \tau \to \ell\pi^+\pi^-\,,\ \tau \to \ell\phi$$

- *Some coherent/incoherent contributions, e.g.:*

$$BR\left(\tau \to \ell\pi^0\right) \propto \sum_{X=L,R} \left| c^{uA}_{\tau\ell X} - c^{dA}_{\tau\ell X} + \frac{m_\pi^2}{m_\tau\left(m_u + m_d\right)}\left(c^{uP}_{\tau\ell X} - c^{dP}_{\tau\ell X}\right)\right|^2$$

$$BR\left(\tau \to \ell\phi\right) \propto \sum_{X=L,R} \left\{ \left(\frac{m_\tau^2}{m_\phi^2} + 1 - 2\frac{m_\phi^2}{m_\tau^2}\right)\left|c^{sV}_{\tau\ell X}\right|^2 + 4\left(\frac{f_{T,\phi}}{f_\phi}\right)^2\left(2\frac{m_\tau^2}{m_\phi^2} - 1 - \frac{m_\phi^2}{m_\tau^2}\right)\left|c^{sT}_{\tau\ell X}\right|^2 \right\}$$

- *Many mesons w/ different structures* — *great complementarity* —

$$\tau \to \ell\pi\,,\ \tau \to \ell\eta\,,\ \tau \to \ell\eta'\,,\ \tau \to \ell\omega\,,\ \tau \to \ell\pi^+\pi^-\,,\ \tau \to \ell\phi$$

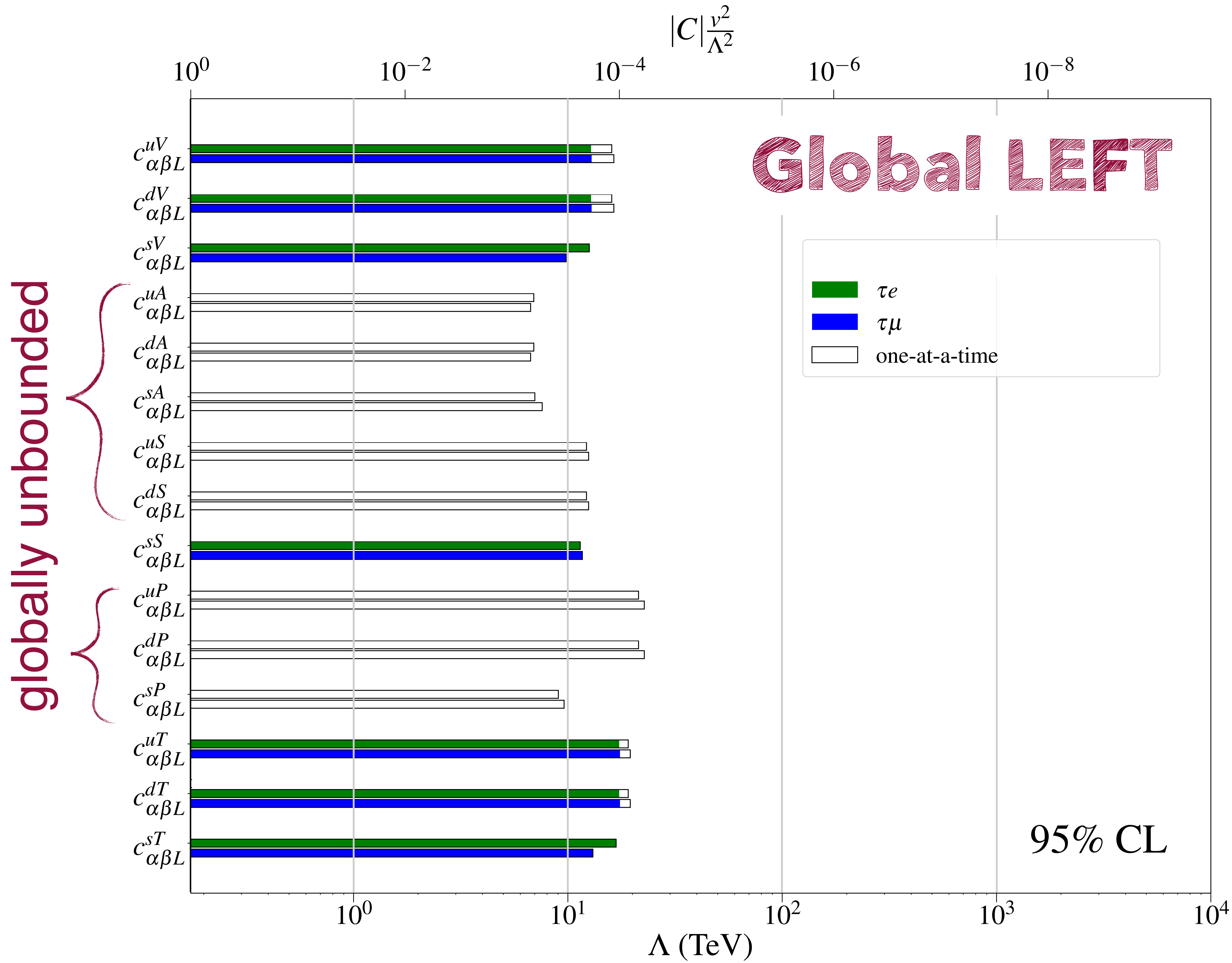
- *Some coherent/incoherent contributions, e.g.:*

Observable	$c^{ux}_{\tau\ell} - c^{dx}_{\tau\ell}$					$c^{ux}_{\tau\ell} + c^{dx}_{\tau\ell}$					$c^{sx}_{\tau\ell}$				
	V	A	S	P	T	V	A	S	P	T	V	A	S	P	T
$\tau \to \ell\pi^0$		1		1											
$\tau \to \ell\eta$							2		2			2		2	
$\tau \to \ell\eta'$							3		3			3		3	
$\tau \to \ell\omega$						4				5					
$\tau \to \ell\pi^+\pi^-$	6				7			8					9		
$\tau \to \ell\phi$											10				11

- *15 WCs - 11 indep. constraints = 4 flat directions*

— *involving A, S and P WCs* —

Semileptonic Operators with taus



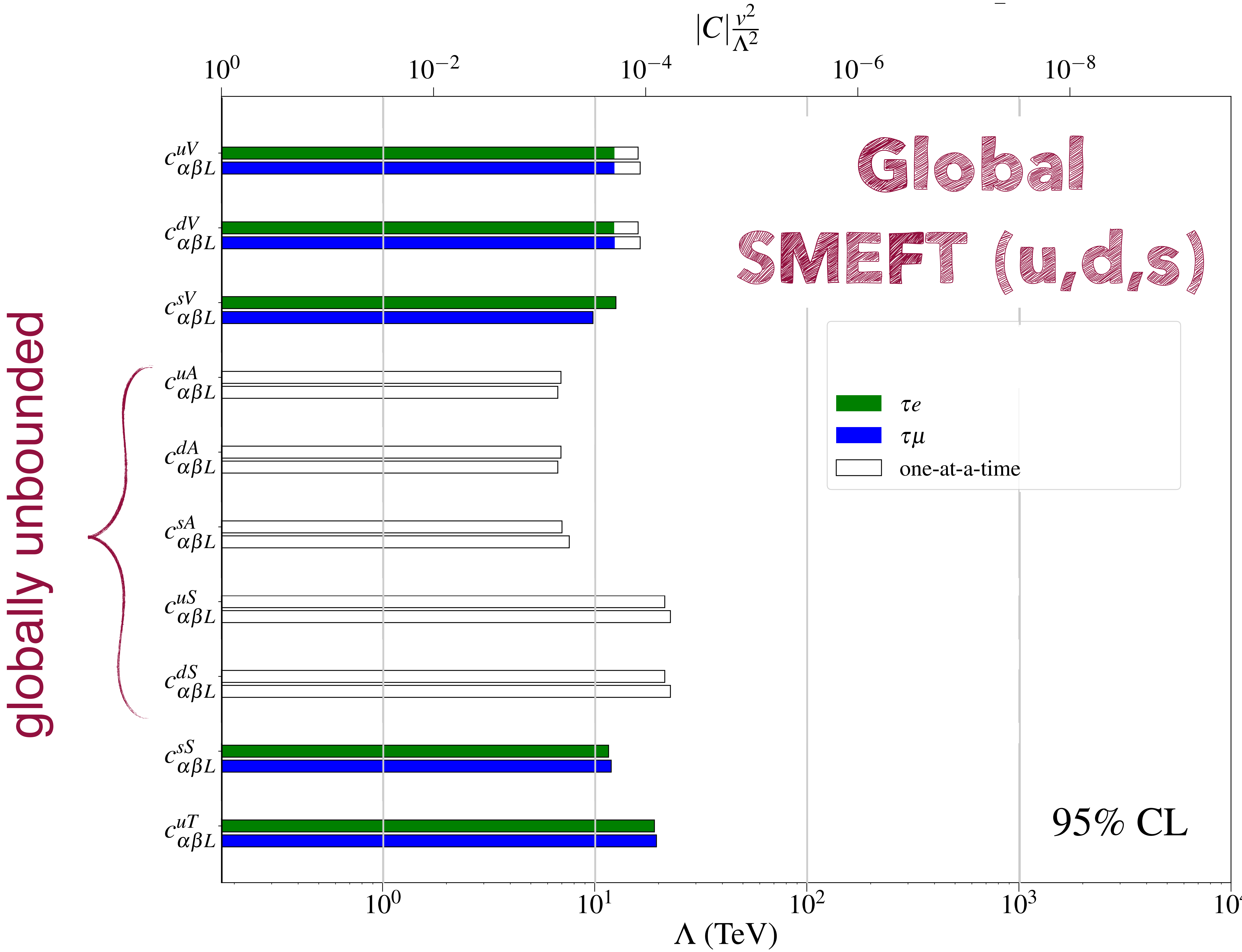
- *In SMEFT things should be simpler…*

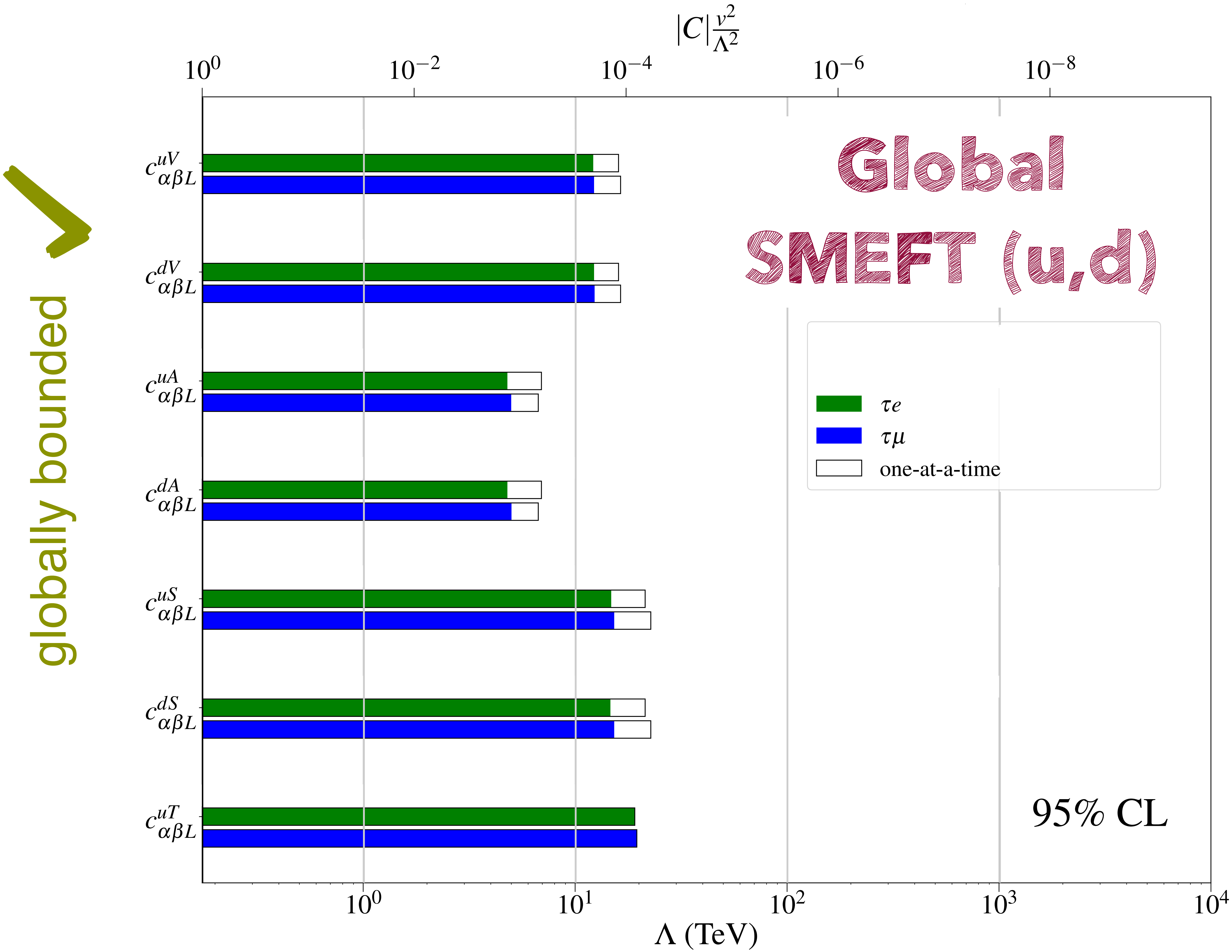
Observable	$c_{\tau\ell}^{ux} - c_{\tau\ell}^{dx}$				$c_{\tau\ell}^{ux} + c_{\tau\ell}^{dx}$				$c_{\tau\ell}^{sx}$		
	V	A	S	T	T	V	A	S	V	A	S
$\tau \to \ell\pi^0$		1						1			
$\tau \to \ell\eta$			2				2			2	2
$\tau \to \ell\eta'$			3				3			3	3
$\tau \to \ell\omega$					5	4					
$\tau \to \ell\pi^+\pi^-$	6			7				8			9
$\tau \to \ell\phi$									10		

- *10 WCs - 9 indep. constraints = 1 flat direction*

— involving A and S WCs —

Semileptonic Operators with taus





$|C|\frac{v^2}{\Lambda^2}$
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
globally bounded
$c^{uV}_{\alpha\beta L}$
$c^{dV}_{\alpha\beta L}$
$c^{uA}_{\alpha\beta L}$
$c^{dA}_{\alpha\beta L}$
$c^{uS}_{\alpha\beta L}$
$c^{dS}_{\alpha\beta L}$
$c^{uT}_{\alpha\beta L}$
Global
SMEFT (u,d)
τe
$\tau\mu$
one-at-a-time
95% CL
10^0
10^1
10^2
10^3
10^4
Λ (TeV)

— Global Results —

	$e\mu$	$\tau\ell$
Fully Leptonic	one-at-a-time bounds = global bounds	
Semileptonic	3	*V and T slightly weaker* *Flat directions for A, S, P* *Only SMEFT(u,d) fully and globally constrained*

- *Very strong constraints*

cLFV obs.	Present upper bounds (90% CL)		
$\mathrm{BR}(\mu \to e\gamma)$	3.1×10^{-13}	MEG II (2023)	[31]
$\mathrm{BR}(\mu \to eee)$	1.0×10^{-12}	SINDRUM (1988)	[32]
$\mathrm{CR}(\mu \to e, \mathrm{S})$	7.0×10^{-11}	Badertscher *et al.* (1982)	[33]
$\mathrm{CR}(\mu \to e, \mathrm{Ti})$	4.3×10^{-12}	SINDRUM II (1993)	[34]
$\mathrm{CR}(\mu \to e, \mathrm{Pb})$	4.6×10^{-11}	SINDRUM II (1996)	[35]
$\mathrm{CR}(\mu \to e, \mathrm{Au})$	7.0×10^{-13}	SINDRUM II (2006)	[36]
$\mathrm{BR}(\pi^0 \to \mu^- e^+)$	3.2×10^{-10}	NA62 (2021)	[37]
$\mathrm{BR}(\pi^0 \to \mu^+ e^-)$	3.8×10^{-10}	E865 (2000)	[38]
$\mathrm{BR}(\pi^0 \to \mu e)$	3.6×10^{-10}	KTeV (2007)	[39]
$\mathrm{BR}(\eta \to \mu e)$	6.0×10^{-6}	Saturne SPES2 (1996)	[40]
$\mathrm{BR}(\eta' \to \mu e)$	4.7×10^{-4}	CLEO (2000)	[41]
$\mathrm{BR}(\phi \to \mu e)$	2.0×10^{-6}	SND (2009)	[42]

Refs in arXiv: 2403.09772

Semileptonic Operators mu-e

- *Very strong constraints*

- *Mainly from $\mu \to e$ conversion in nuclei*

  - *Spin-Independent for V, S, T operators*

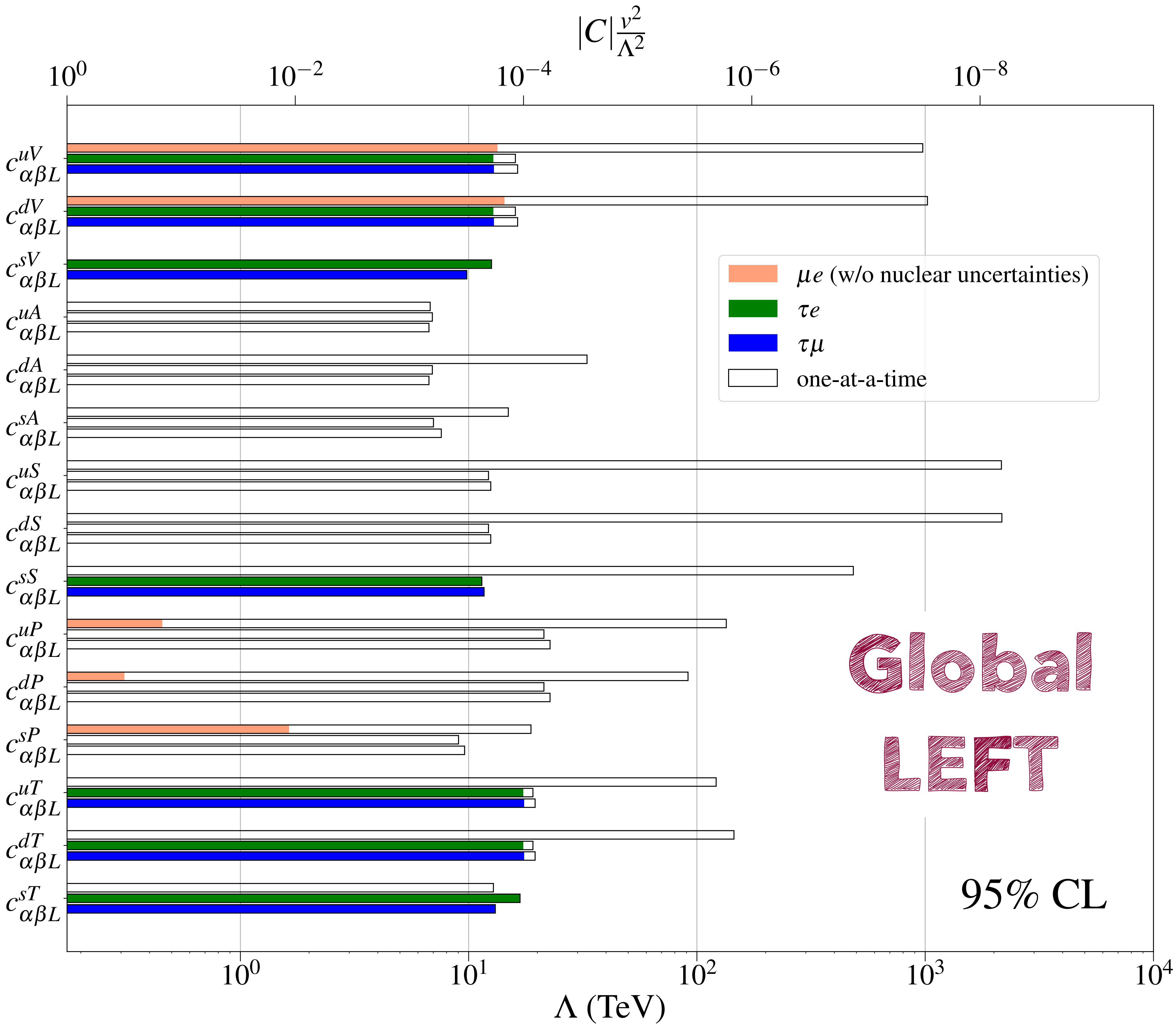
    — e.g. Raidal'97,Cirigliano'09,Crivellin'17,Davidson'22,Plakias'23… —

  - *Spin-Dependent for A, P, T operators*

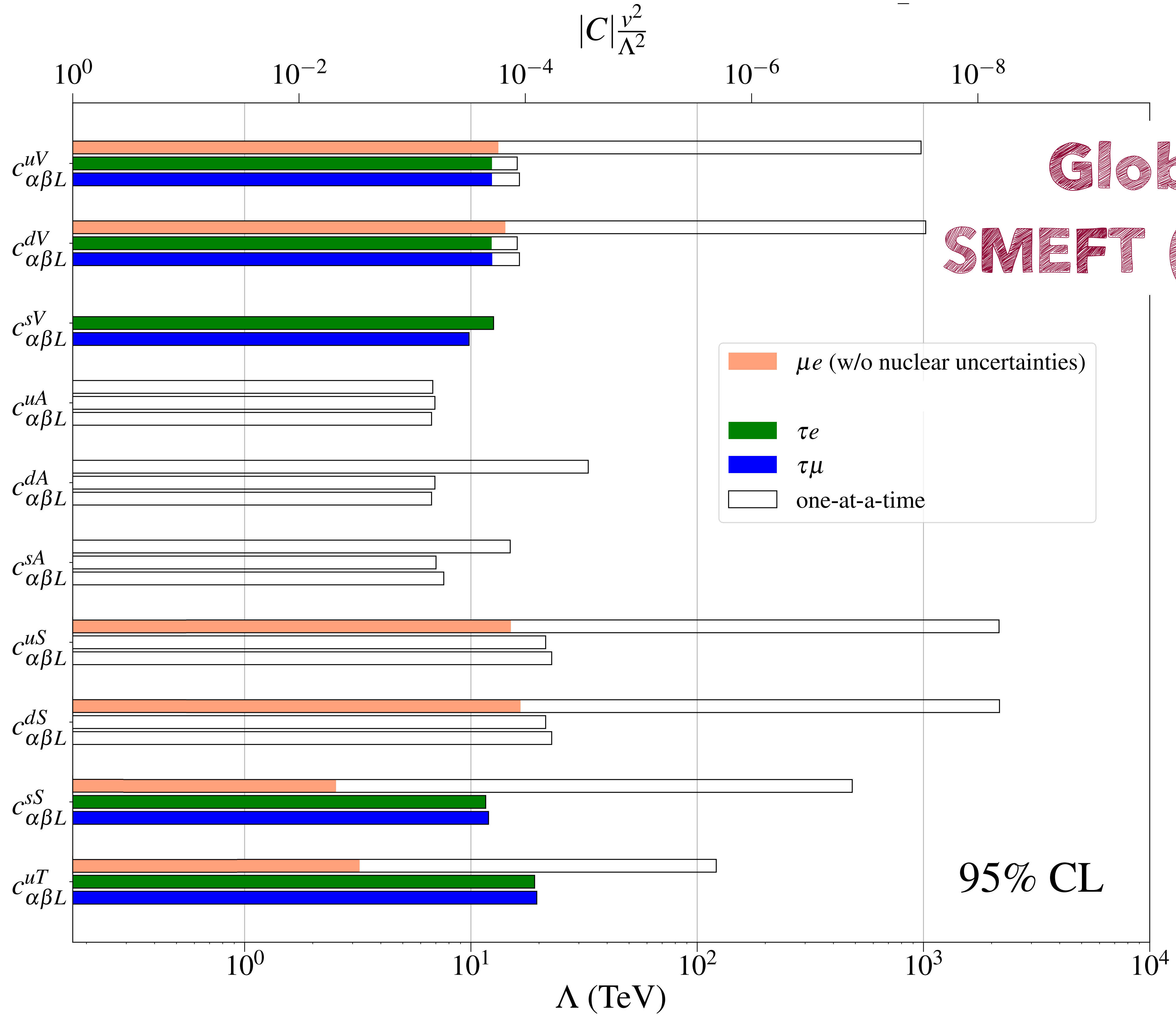
    — Cirigliano'17, Davidson '17, Hoferichter '22 —

- *Weaker but complementary from $M \to e\mu$ for A and P*

Semileptonic Operators mu-e



Semileptonic Operators mu-e



Global SMEFT (u,d,s)

Nuclear Uncertainties in mu-e conv

- *These results rely* ***crucially*** *on nuclear elements for* $\mu \to e$ *conv.*

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- *Uncertainties of the overlap integrals can make bounds redundant*

— Davidson et al [1810.01884] —

$$\left.\begin{aligned} \mathrm{CR}(\mu \to e, \mathrm{S}) &< 7.0 \times 10^{-11} \\ \mathrm{CR}(\mu \to e, \mathrm{Ti}) &< 4.3 \times 10^{-12} \\ \mathrm{CR}(\mu \to e, \mathrm{Pb}) &< 4.6 \times 10^{-11} \\ \mathrm{CR}(\mu \to e, \mathrm{Au}) &< 7.0 \times 10^{-13} \end{aligned}\right\}$$

All independent bounds?

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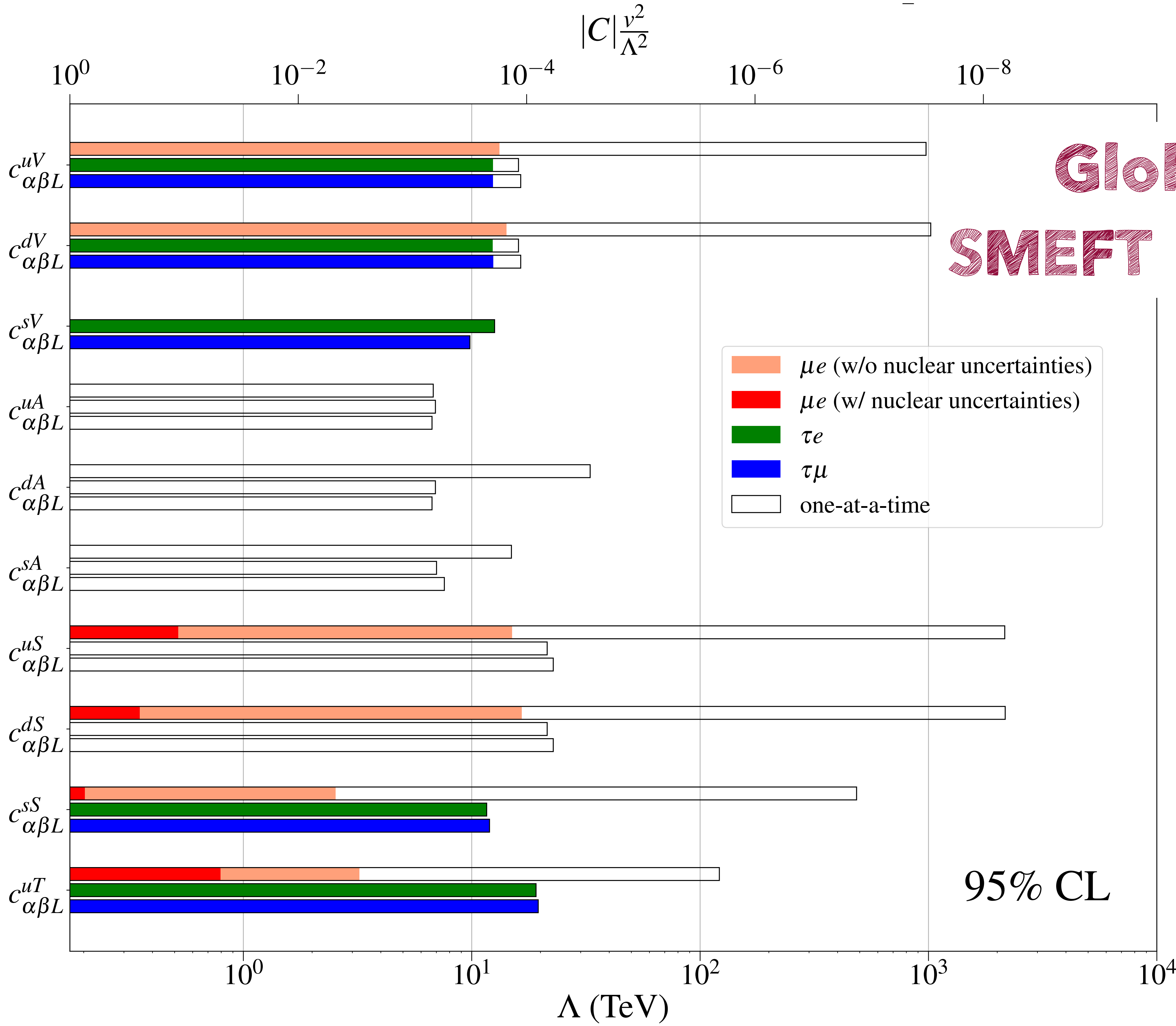
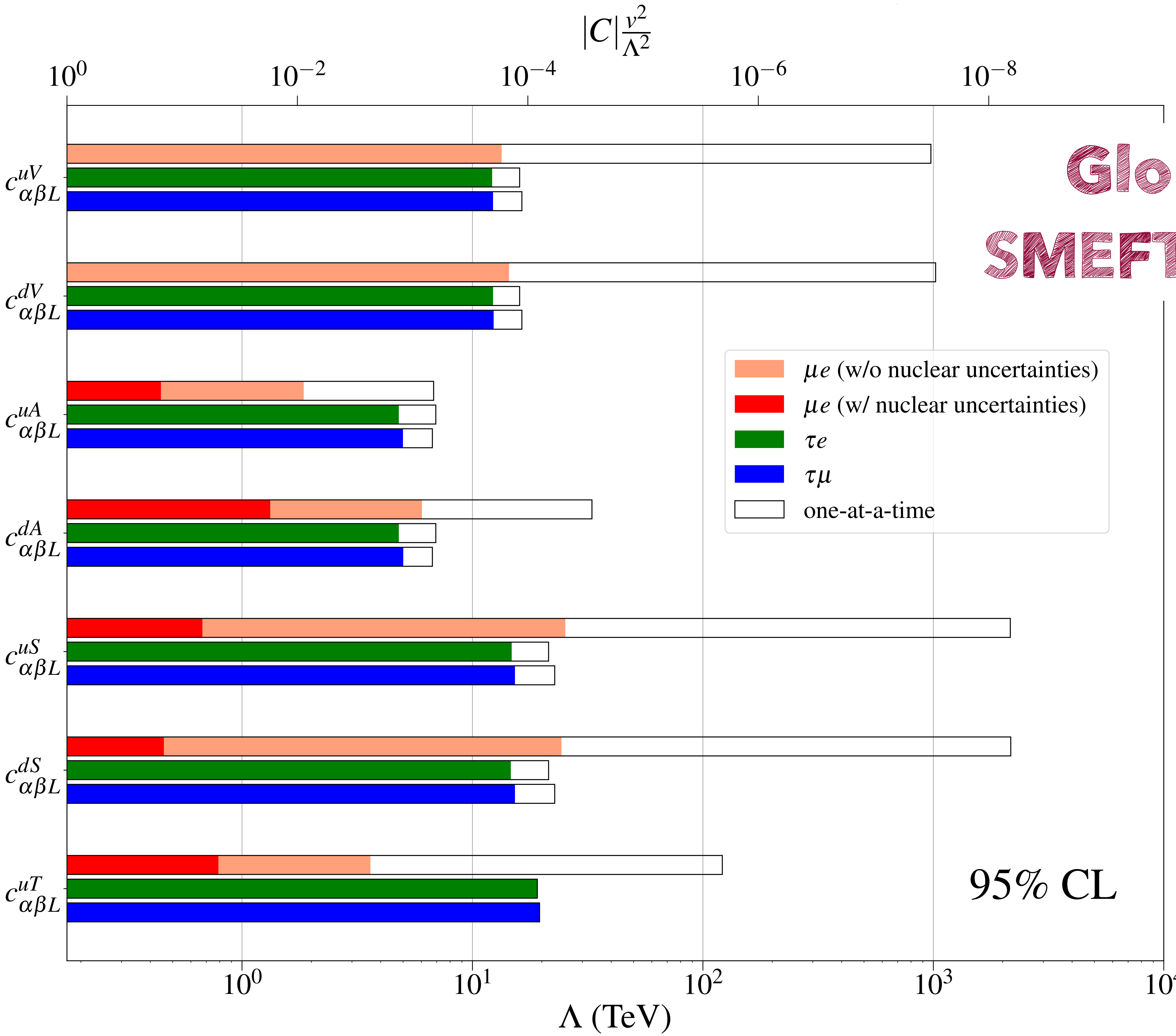
All independent bounds?

- *We include nuclear uncertainties as nuisance parameters in the GF*



Global SMEFT (u,d,s)

Semileptonic Operators mu-e



Global SMEFT (u,d)

— Global Results —

	$e\mu$	$\tau\ell$
Fully Leptonic	one-at-a-time bounds = global bounds	
Semileptonic	- *Global analysis has* ***strong impact*** - ***Nuclear uncertainties*** *even stronger* - *None of the scenarios fully constrained*	- *V and T slightly weaker* - *Flat directions for A, S, P* - *Only SMEFT(u,d) fully and globally constrained*

Summary

- *Very strong cLFV bounds when consider each operator at a time*

  — *bounds* $(\mu \to e) \gg$ *bounds* $(\tau \to \ell)$ —

- *Global picture changes things for semileptonic operators:*

  - *Flat directions in* $\tau\ell$ *sectors for A, S, P*

    — *only the simplest SMEFT(u,d) fully constrained* —

  - *Strong impact in the* μe *sector*

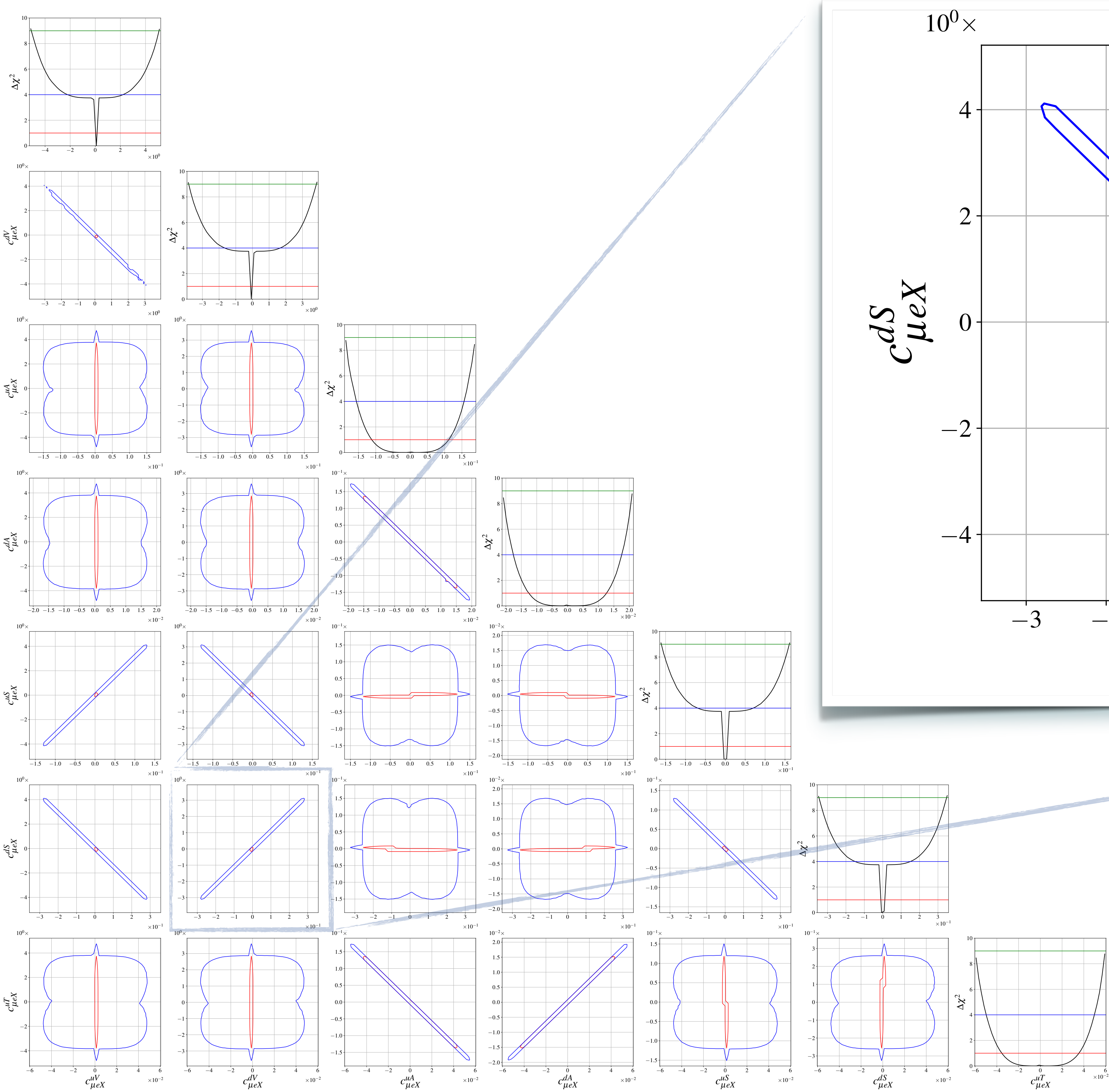
    — *bounds* $(\mu \to e) \sim$ *bounds* $(\tau \to \ell)$ —

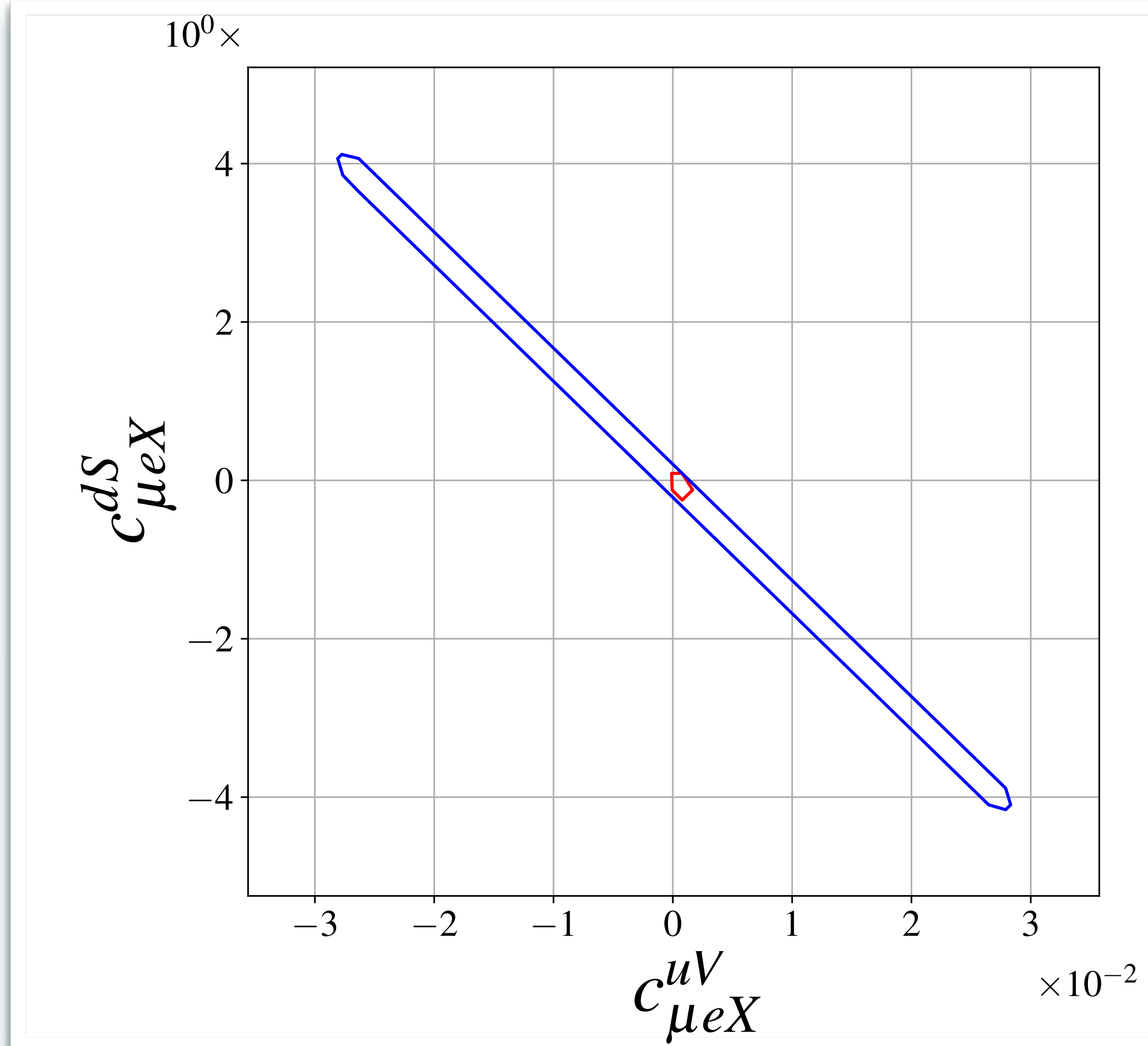
- *Nuclear uncertainties have a key role*

  — *bounds* $(\mu \to e) \ll$ *bounds* $(\tau \to \ell)$ —

Does this mean there are unbounded operators?

Strong Correlations





Check
arXiv: 2403.09772
for
'correlation' matrices

Thank you!

Funded by the European Union's Horizon Europe Programme under the Marie Skłodowska-Curie grant agreement no. 101066105-PheNUmenal. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Executive Agency (REA). Neither the European Union nor the granting authority can be held responsible for them.

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PheNumenal

EXCELENCIA SEVERO OCHOA

BACK UP

Nuclear Uncertainties

- *Nuclear overlap integrals for SI at 5% (10%) for light (heavy) nuclei*

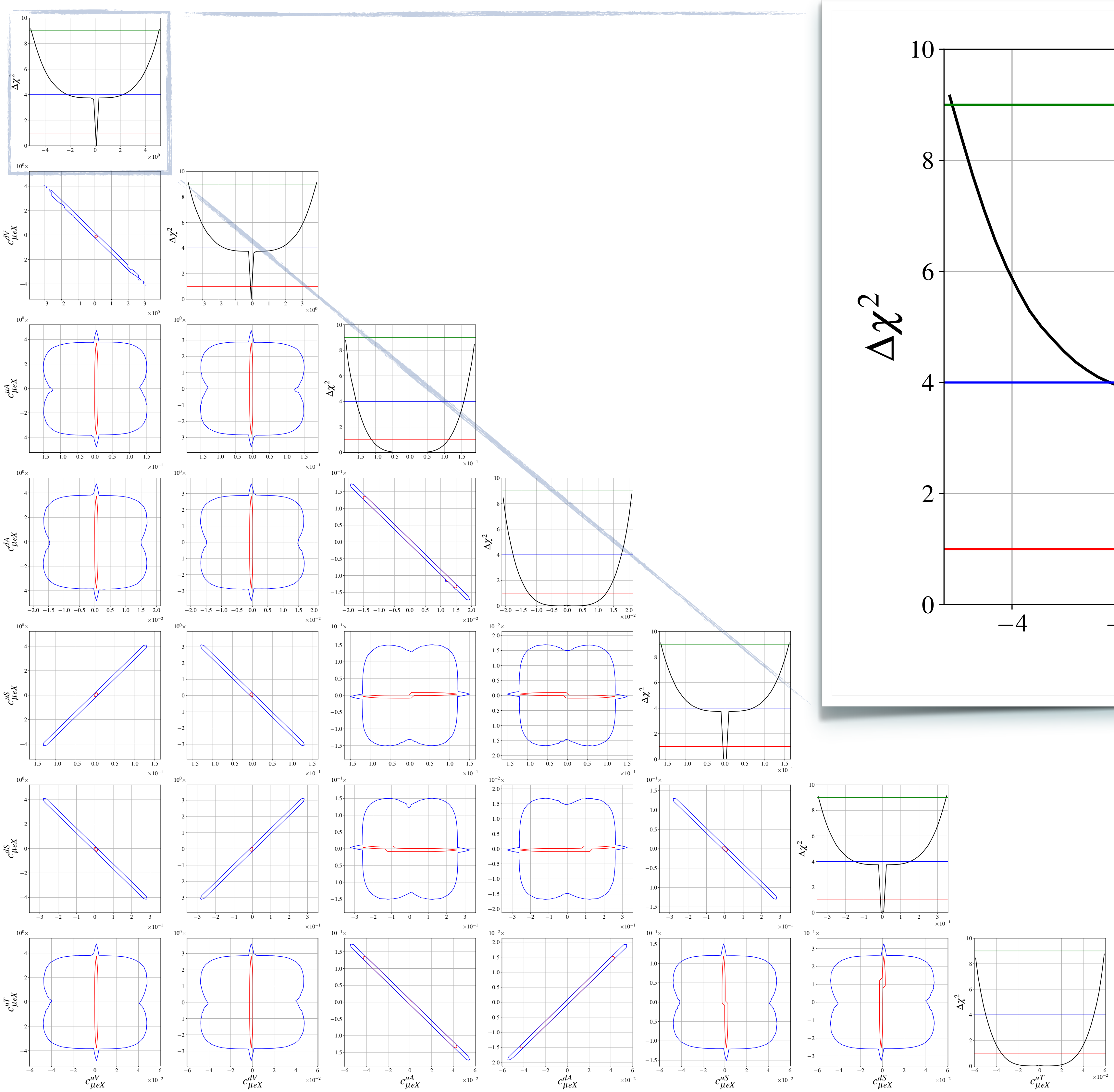
  — Davidson et al [1710.06787], Hoferichter et al [1506.04142], Bartolotta et al [1710.02129]—

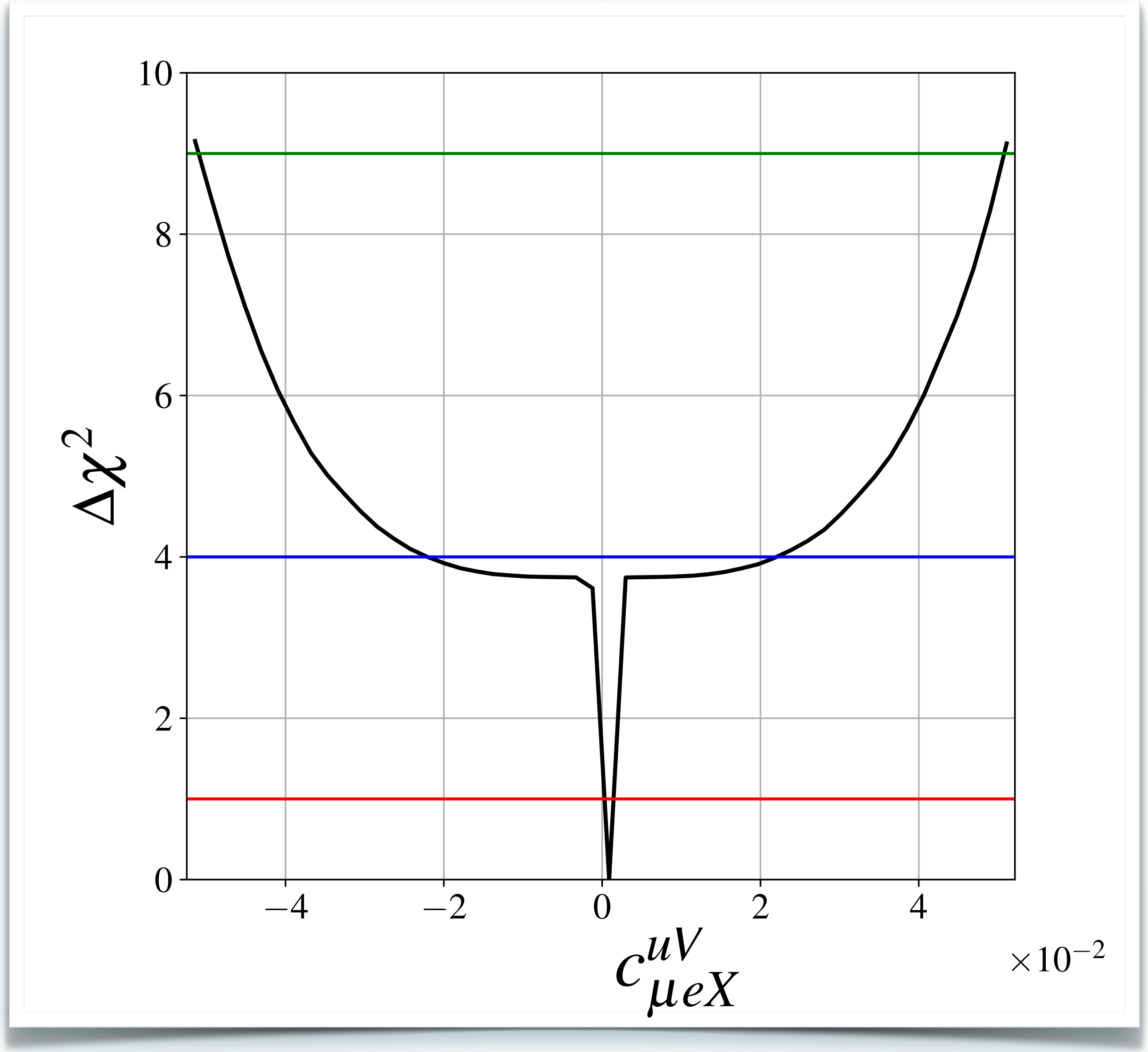
- *Nuclear corrections δ' and δ'' to the axial contribution of SD*

  — Hoferichter et al [2204.06005]—

- *Gluonic matrix element $\tilde{a}_N \sim$ 30%*

  — Hoferichter et al [2204.06005]—


$\Delta\chi^2$
$c^{dV}_{\mu eX}$
$c^{uA}_{\mu eX}$
$c^{dA}_{\mu eX}$
$c^{uS}_{\mu eX}$
$c^{dS}_{\mu eX}$
$c^{uT}_{\mu eX}$
$c^{uV}_{\mu eX}$


$\Delta\chi^2$
$c^{uV}_{\mu eX}$
$\times 10^{-2}$

Semileptonic tau decays

$$\mathrm{BR}\left(\tau \to \ell \pi^0\right) = \frac{G_F^2 f_\pi^2 (m_\tau^2 - m_\pi^2)^2}{8\pi \Gamma_\tau m_\tau} \sum_{X=L,R} \left| c_{\tau\ell X}^{uA} - c_{\tau\ell X}^{dA} + \frac{m_\pi^2}{m_\tau \left(m_u + m_d\right)} \left(c_{\tau\ell X}^{uP} - c_{\tau\ell X}^{dP}\right) \right|^2$$

— Aebischer et al [1810.07698]—

$$\mathrm{BR}\left(\tau \to \ell \pi^+ \pi^-\right) = \sum_{X=L,R} \left\{ 2.0 \left| c_{\tau\ell X}^{uV} - c_{\tau\ell X}^{dV} \right|^2 + 0.68 \left| c_{\tau\ell X}^{uS} + c_{\tau\ell X}^{dS} \right|^2 + 0.52 \left| c_{\tau\ell X}^{sS} \right|^2 + 4.0 \left| c_{\tau\ell X}^{uT} - c_{\tau\ell X}^{dT} \right|^2 \right\}$$

— Cirigliano et al [2102.06176]—

$$\mathrm{BR}\left(\tau \to \ell \omega\right) = \frac{G_F^2 f_\omega^2 m_\omega^2 (m_\tau^2 - m_\omega^2)}{8\pi \Gamma_\tau m_\tau} \sum_{X=L,R} \left\{ \left(\frac{m_\tau^2}{m_\omega^2} + 1 - 2\frac{m_\omega^2}{m_\tau^2} \right) \left| c_{\tau\ell X}^{uV} + c_{\tau\ell X}^{dV} \right|^2 + 4 \left(\frac{f_{T,\omega}}{f_\omega} \right)^2 \left(2\frac{m_\tau^2}{m_\omega^2} - 1 - \frac{m_\omega^2}{m_\tau^2} \right) \left| c_{\tau\ell X}^{uT} + c_{\tau\ell X}^{dT} \right|^2 \right\}.$$

— Aebischer et al [1810.07698]—

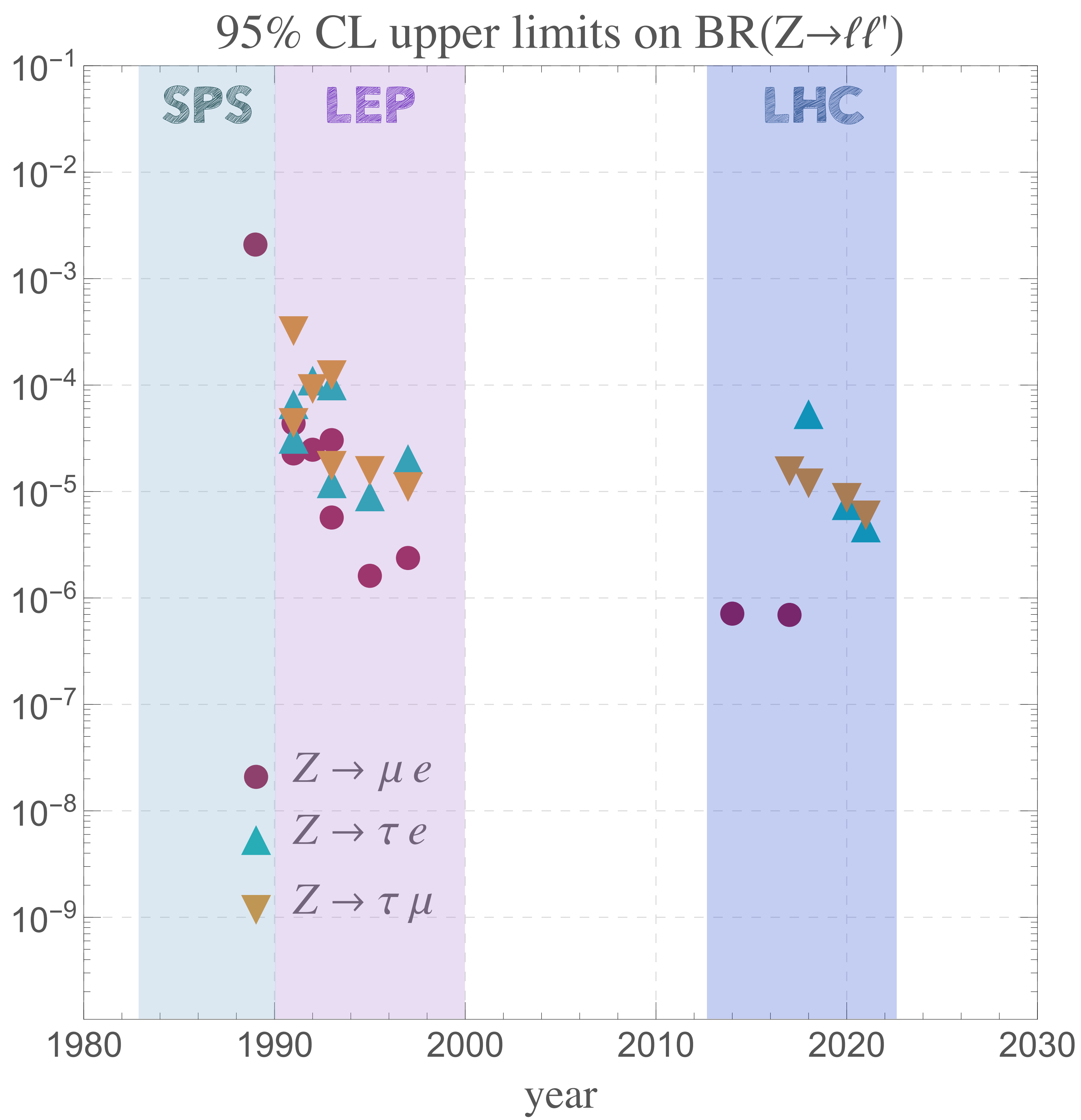
$$\mathrm{BR}\left(\tau\to\ell\eta\right)=\frac{G_F^2 f_\pi^2\left(m_\tau^2-m_\eta^2\right)^2}{8\pi\Gamma_\tau m_\tau}\sum_{X=L,R}\left|\frac{f_\eta^u}{f_\pi}\left(c_{\tau\ell X}^{uA}+c_{\tau\ell X}^{dA}\right)+\frac{f_\eta^s}{f_\pi}c_{\tau\ell X}^{sA}\right.$$
$$\left.+\frac{h_\eta^u}{f_\pi m_\tau(m_u+m_d)}\left(c_{\tau\ell X}^{uP}+c_{\tau\ell X}^{dP}\right)+\frac{h_\eta^s}{2f_\pi m_\tau m_s}c_{\tau\ell X}^{sP}\right|^2,$$

$$\mathrm{BR}\left(\tau\to\ell\eta'\right)=\frac{G_F^2 f_\pi^2\left(m_\tau^2-m_{\eta'}^2\right)^2}{8\pi\Gamma_\tau m_\tau}\sum_{X=L,R}\left|\frac{f_{\eta'}^u}{f_\pi}\left(c_{\tau\ell X}^{uA}+c_{\tau\ell X}^{dA}\right)+\frac{f_{\eta'}^s}{f_\pi}c_{\tau\ell X}^{sA}\right.$$
$$\left.+\frac{h_{\eta'}^u}{f_\pi m_\tau(m_u+m_d)}\left(c_{\tau\ell X}^{uP}+c_{\tau\ell X}^{dP}\right)+\frac{h_{\eta'}^s}{2f_\pi m_\tau m_s}c_{\tau\ell X}^{sP}\right|^2.$$

— Celis et al [1403.5781]—

$$\mathrm{BR}\left(\tau\to\ell\phi\right)=\frac{G_F^2 f_\phi^2 m_\phi^2(m_\tau^2-m_\phi^2)}{4\pi\Gamma_\tau m_\tau}\sum_{X=L,R}\left\{\left(\frac{m_\tau^2}{m_\phi^2}+1-2\frac{m_\phi^2}{m_\tau^2}\right)\left|c_{\tau\ell X}^{sV}\right|^2\right.$$
$$\left.+4\left(\frac{f_{T,\phi}}{f_\phi}\right)^2\left(2\frac{m_\tau^2}{m_\phi^2}-1-\frac{m_\phi^2}{m_\tau^2}\right)\left|c_{\tau\ell X}^{sT}\right|^2\right\},$$

— Aebischer et al [1810.07698]—


95% CL upper limits on BR(Z→ℓℓ')
SPS
LEP
LHC
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
$Z \to \mu e$
$Z \to \tau e$
$Z \to \tau \mu$
1980
1990
2000
2010
2020
2030
year

— *Calibbi, XM, Roy [2107.10273]* —