ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Newtrinos
Effective Portals to New Physics

INFN

Can neutrinos help probing the SM effective theory?

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Ministero
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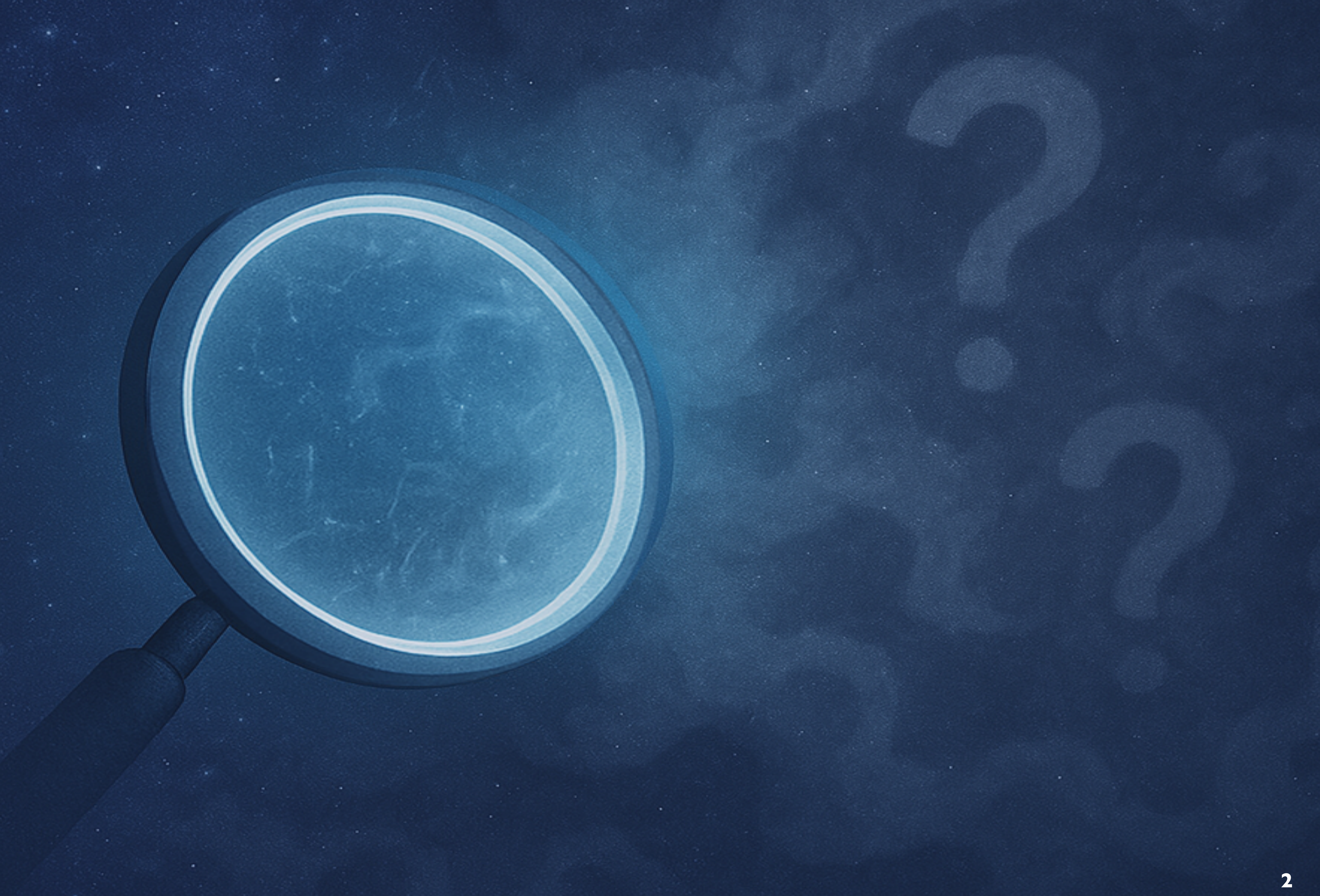
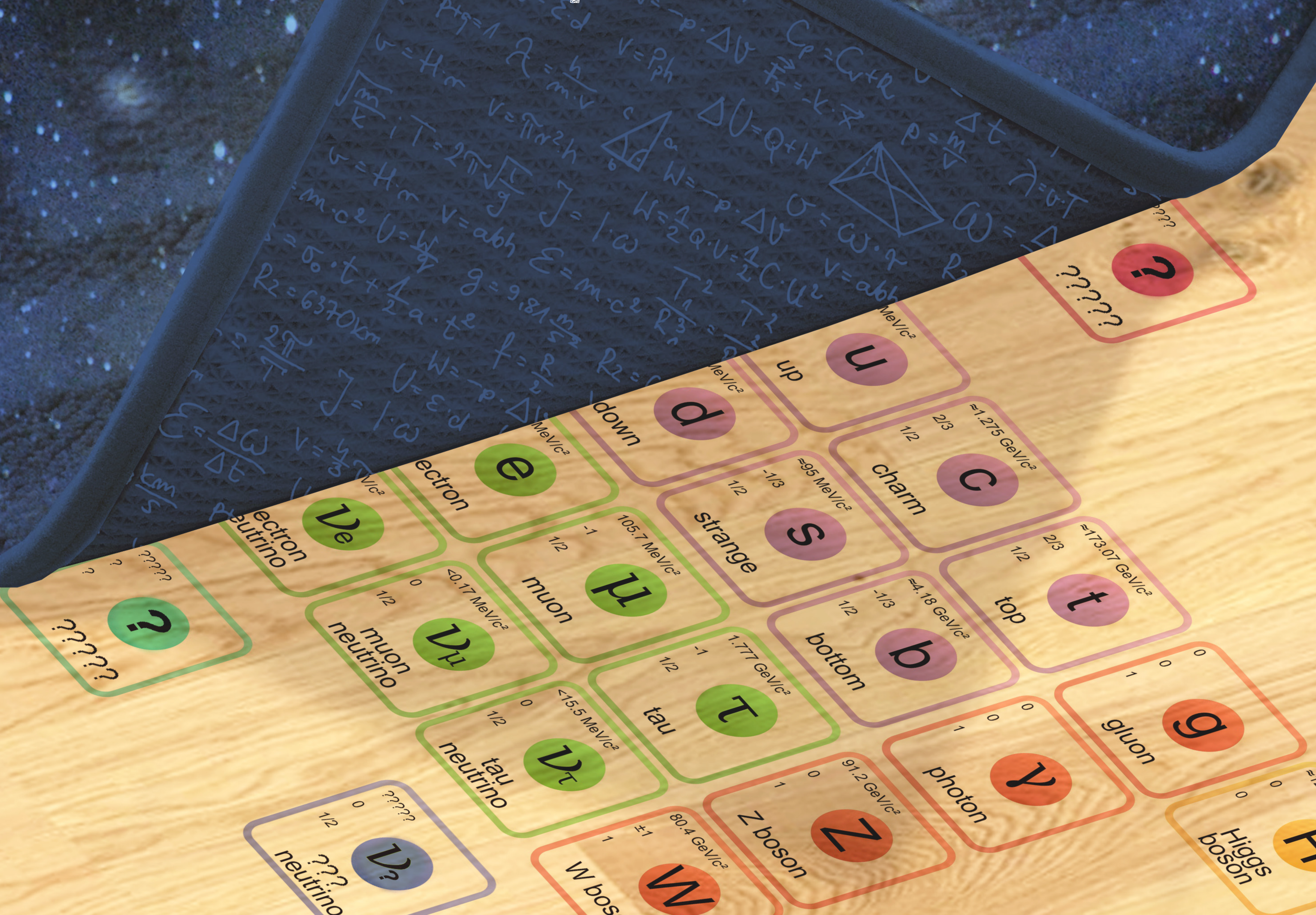
e della Ricerca

Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA

ONCE UPON A TIME . . .

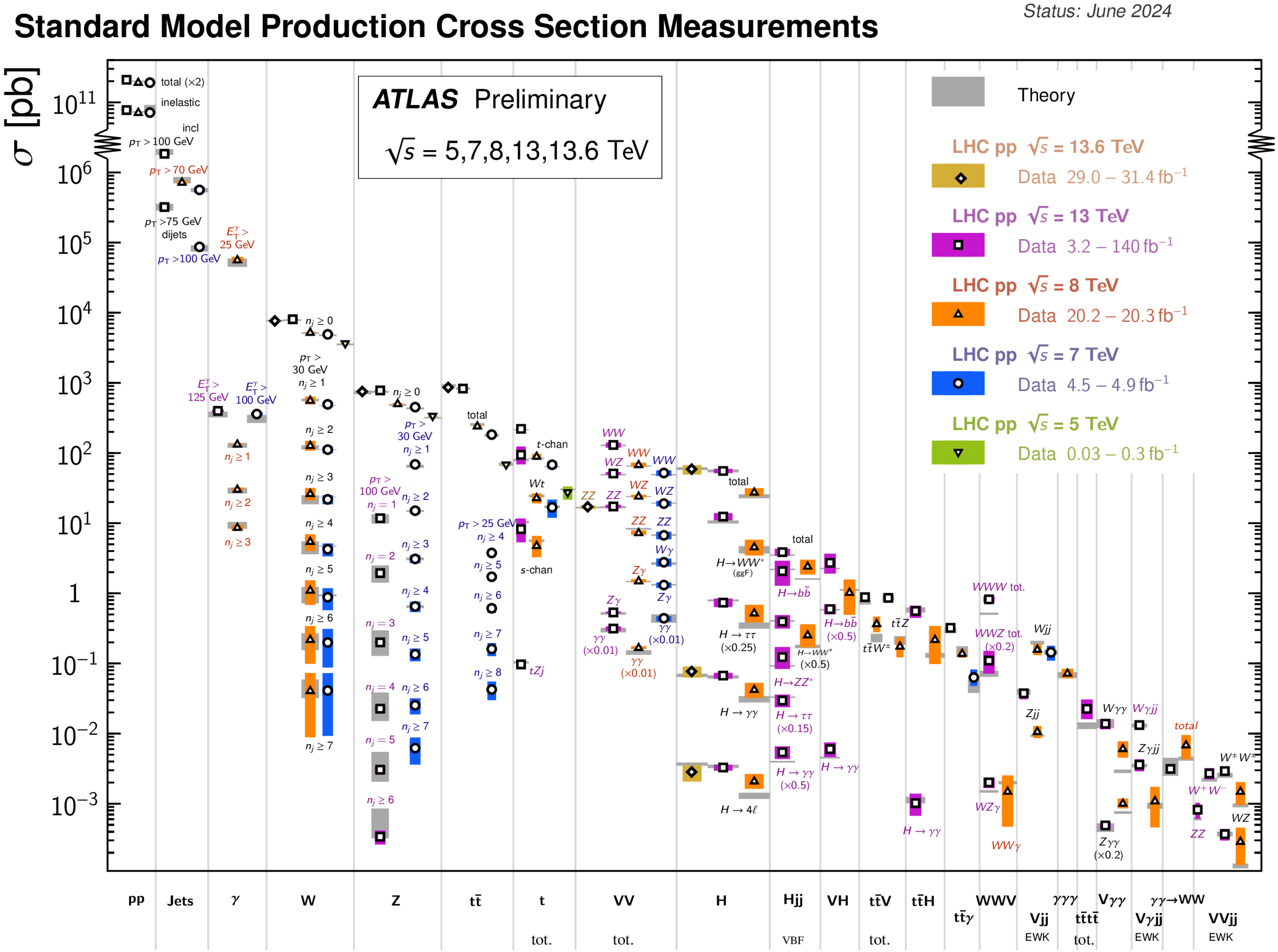


ONCE UPON A TIME, THERE WAS A THEORY



Once upon a time, there was a theory

WHO RULED US ALL



OR ALMOST

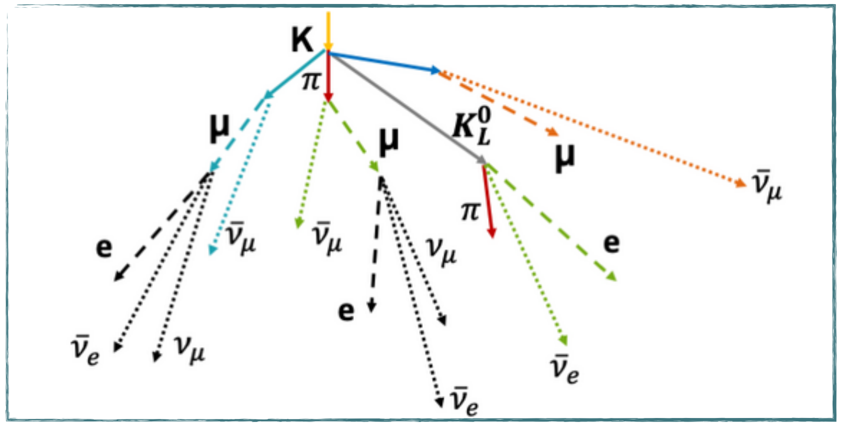
— Open Problems in the SM —

- *Neutrino masses*
- *Dark Matter*
- *Baryon Asymmetry of the Universe*
- *Strong CP problem*
- *Hierarchy problem*
- *Flavor puzzle*
- …

NEUTRINO MASSES

Neutrino Oscillations: Solution of two open problems

- Atmospheric Neutrino Problem

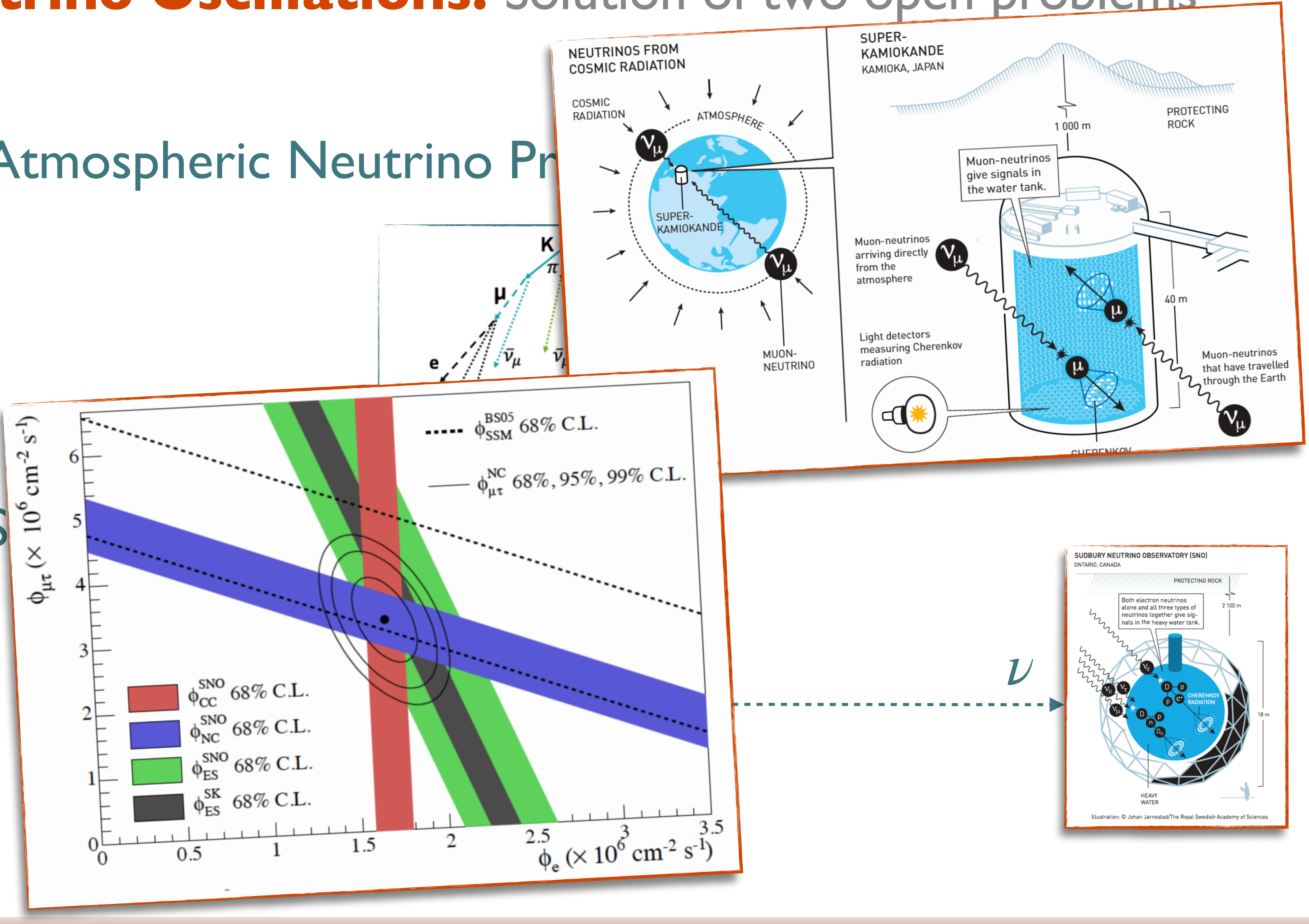


- Solar Neutrino Problem

Neutrino Oscillations: Solution of two open problems

- Atmospheric Neutrino Pr

- S



Muon-neutrinos give signals in the water tank.

Muon-neutrinos arriving directly from the atmosphere

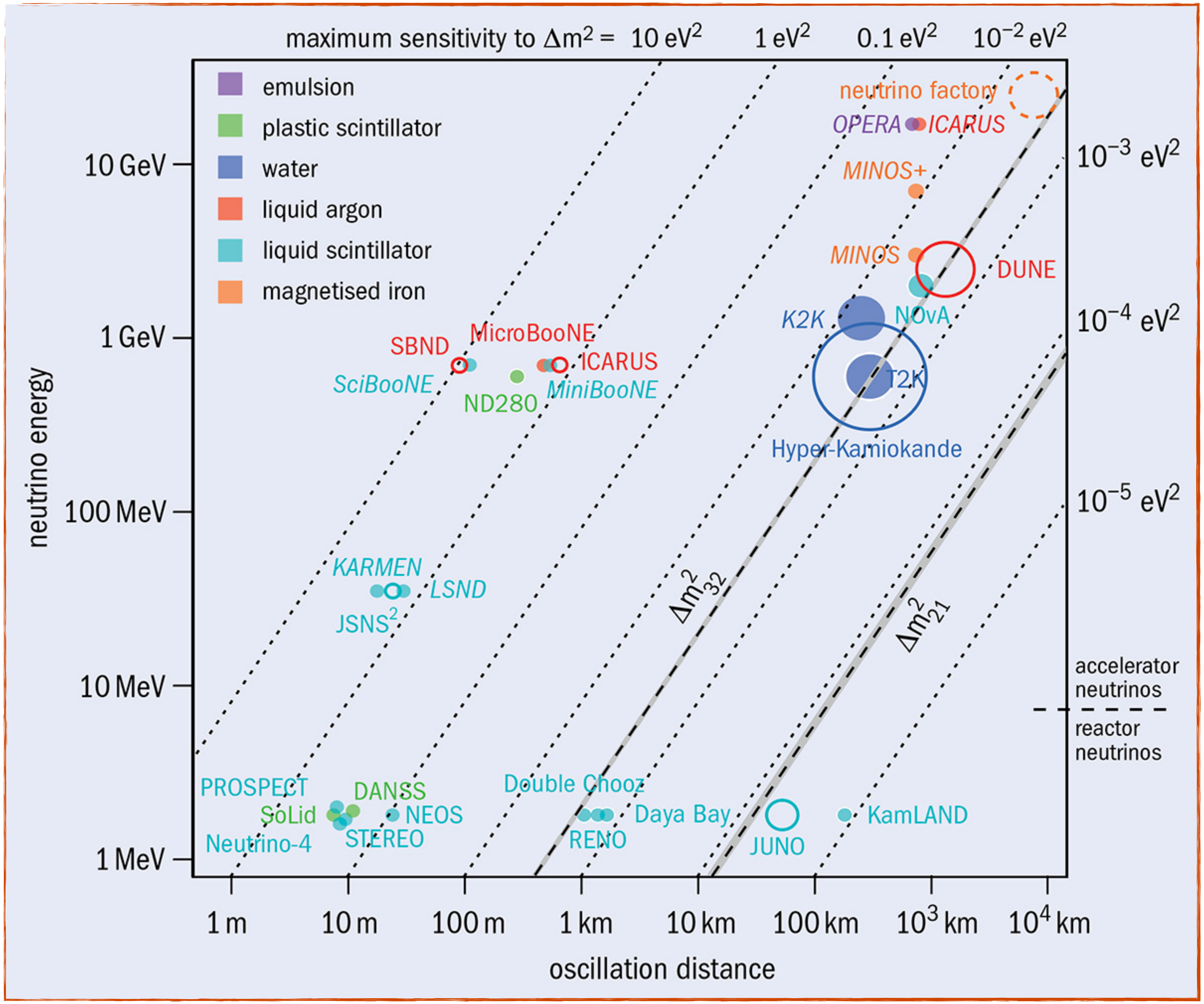
Light detectors measuring Cherenkov radiation

Muon-neutrinos that have travelled through the Earth

Both electron neutrinos alone and all three types of neutrinos together give signals in the heavy water tank.

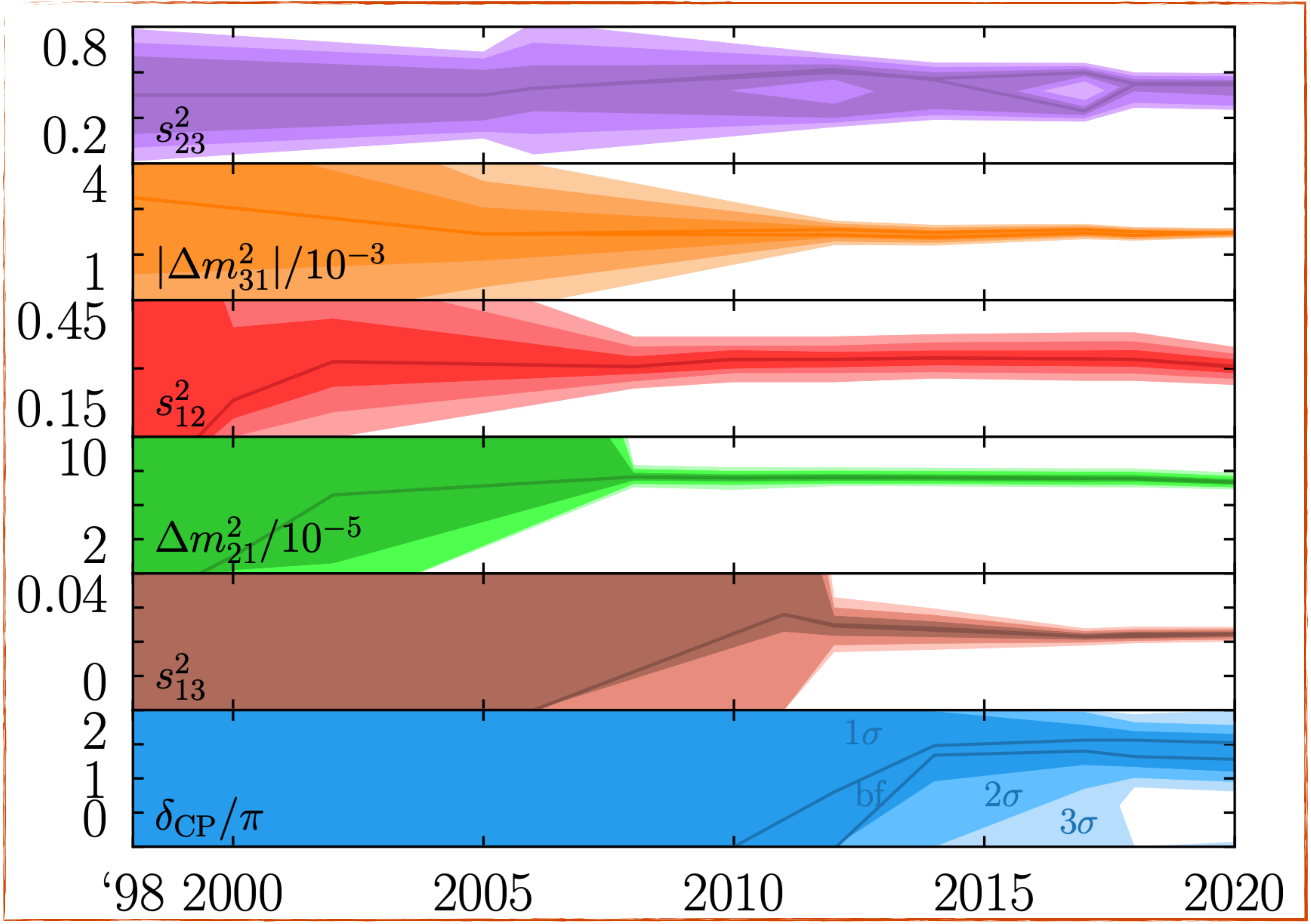
Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

NEUTRINO OSC. EXPERIMENTS



NEUTRINO OSC. EXPERIMENTS

Denton et al [2212.00809]



NEW PARTICLES?

— OPEN PROBLEMS IN THE SM —

- *Neutrino masses* ⟶ **New Physics**
- *Dark Matter*
- *Baryon Asymmetry of the Universe*
- *Strong CP problem*
- *Hierarchy problem*
- *Flavor puzzle*
- …

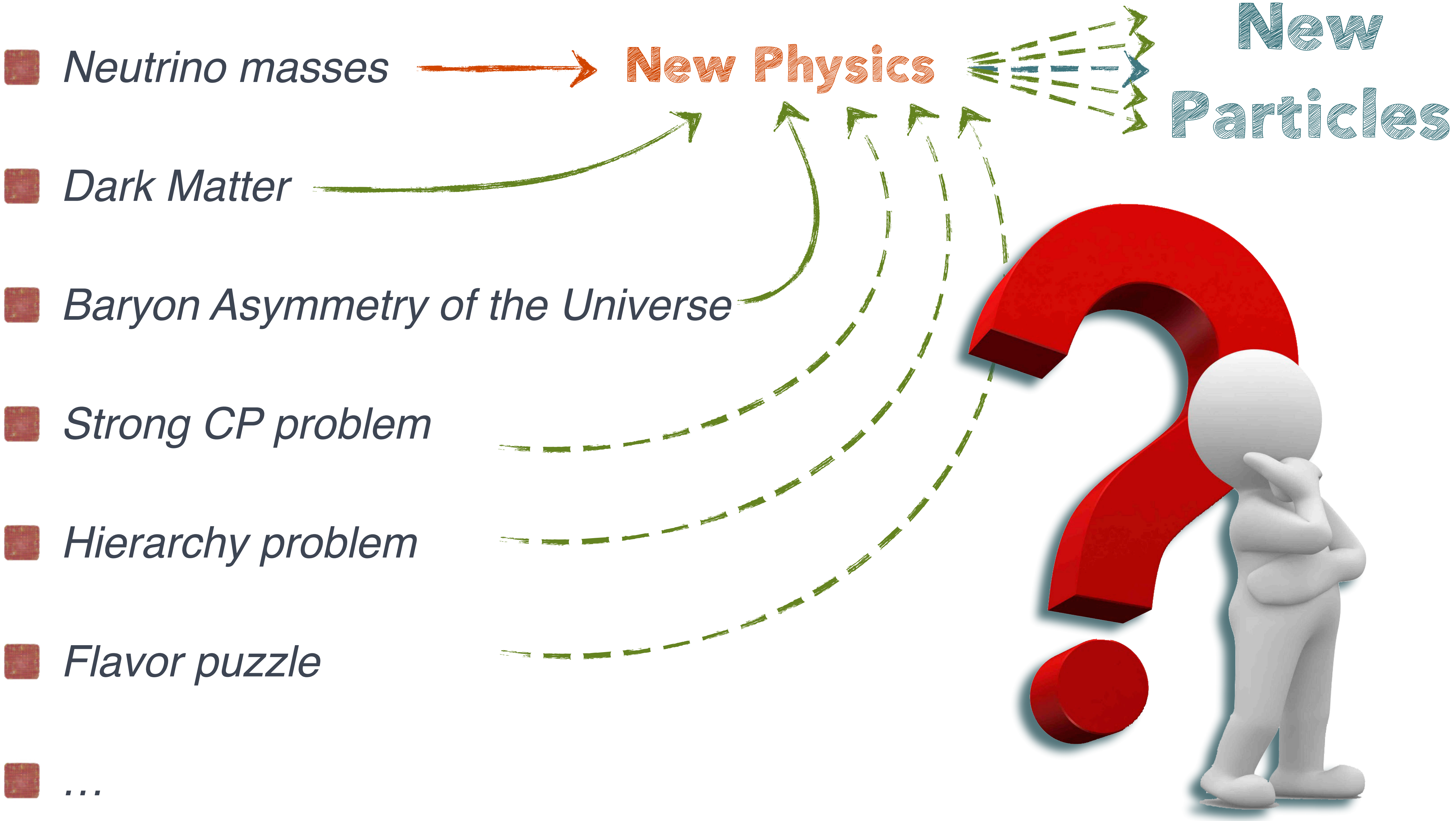
NEW PARTICLES?

— OPEN PROBLEMS IN THE SM —

- *Neutrino masses* ⟶ **New Physics** - - - -> **New Particles**
- *Dark Matter*
- *Baryon Asymmetry of the Universe*
- *Strong CP problem*
- *Hierarchy problem*
- *Flavor puzzle*
- *…*

NEW PARTICLES?

— OPEN PROBLEMS IN THE SM —



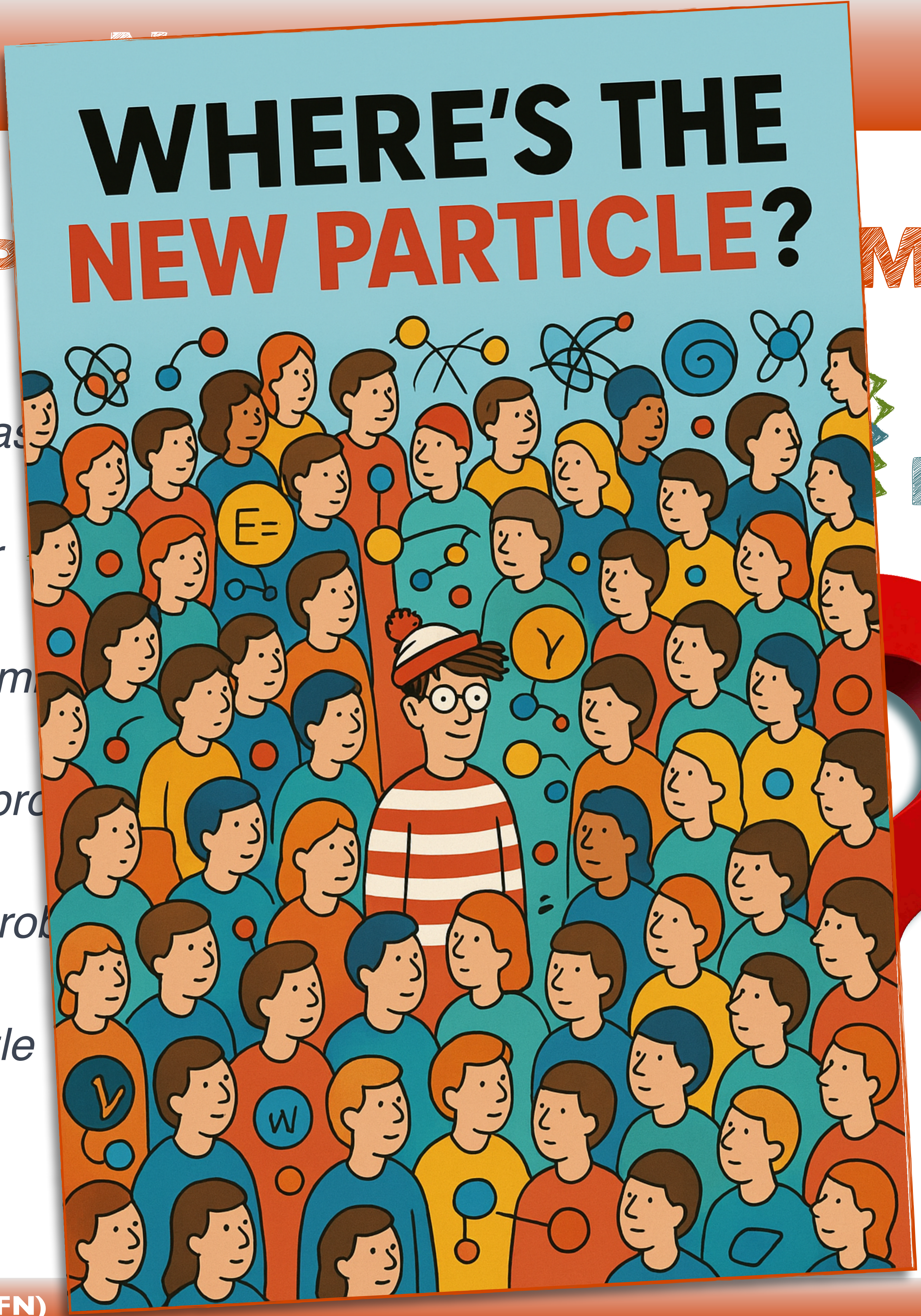
- *Neutrino masses*
- *Dark Matter*
- *Baryon Asymmetry of the Universe*
- *Strong CP problem*
- *Hierarchy problem*
- *Flavor puzzle*
- …

New Physics

New Particles

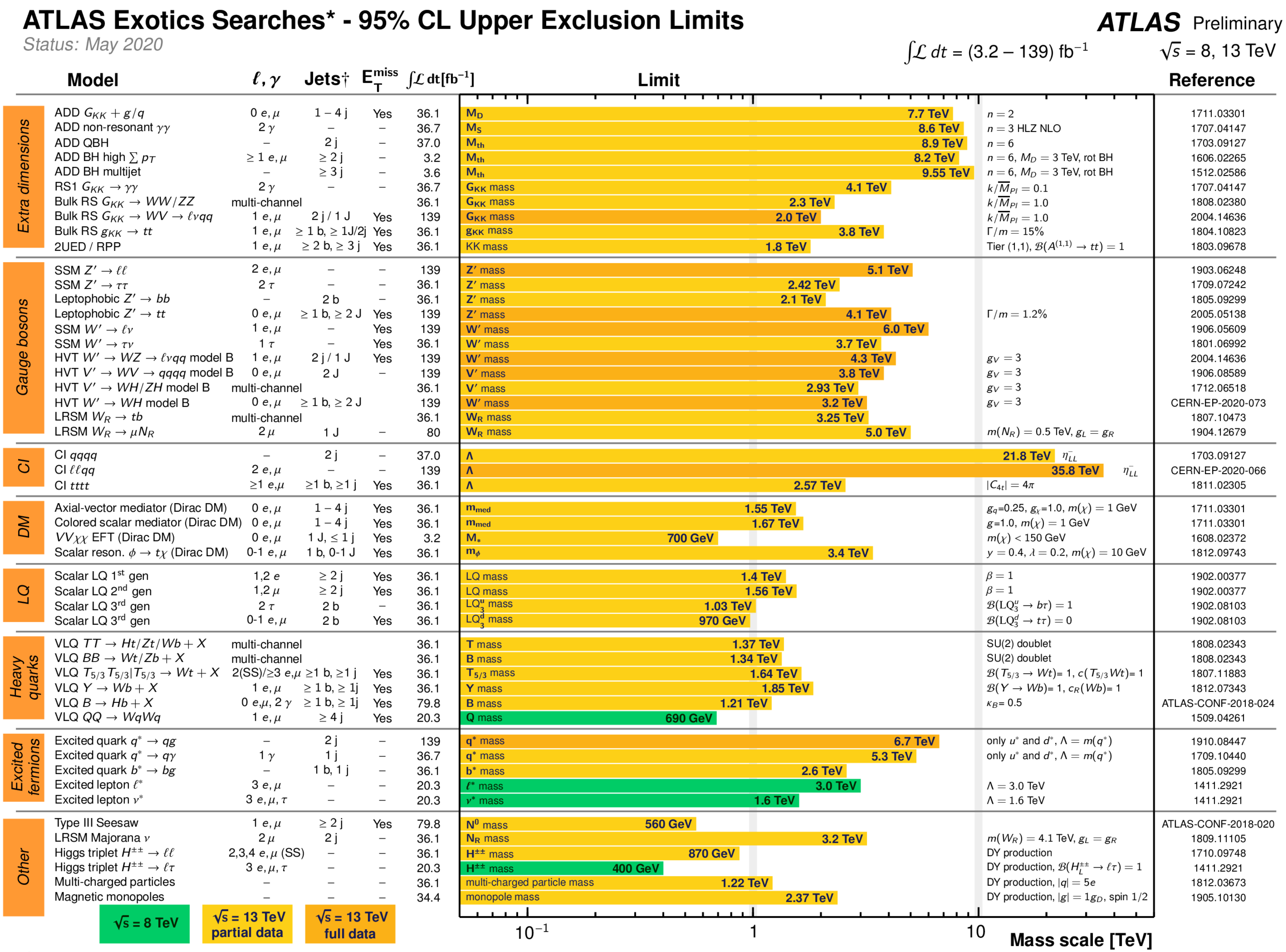
— OP M —

- Neutrino mas
- Dark Matter
- Baryon Asym
- Strong CP pro
- Hierarchy prob
- Flavor puzzle
- …



New Particles

NO SIGNALS OF NEW PHYSICS



ATLAS Exotics Searches* - 95% CL Upper Exclusion Limits

Status: May 2020

ATLAS Preliminary

$\int\mathcal{L}\,dt = (3.2 - 139)$ fb^{-1}

$\sqrt{s} = 8, 13$ TeV

	Model	ℓ, γ	Jets†	E_T^{miss}	$\int\mathcal{L}\,dt[\text{fb}^{-1}]$	Limit		Reference
Extra dimensions	ADD $G_{KK} + g/q$	0 e, μ	$1 - 4$ j	Yes	36.1	M_D 7.7 TeV	$n = 2$	1711.03301
	ADD non-resonant $\gamma\gamma$	2 γ	–	–	36.7	M_S 8.6 TeV	$n = 3$ HLZ NLO	1707.04147
	ADD QBH	–	2 j	–	37.0	M_{th} 8.9 TeV	$n = 6$	1703.09127
	ADD BH high $\sum p_T$	≥ 1 e, μ	≥ 2 j	–	3.2	M_{th} 8.2 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1606.02265
	ADD BH multijet	–	≥ 3 j	–	3.6	M_{th} 9.55 TeV	$n = 6$, $M_D = 3$ TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$	2 γ	–	–	36.7	G_{KK} mass 4.1 TeV	$k/\overline{M}_{Pl} = 0.1$	1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi-channel			36.1	G_{KK} mass 2.3 TeV	$k/\overline{M}_{Pl} = 1.0$	1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1 e, μ	2 j / 1 J	Yes	139	G_{KK} mass 2.0 TeV	$k/\overline{M}_{Pl} = 1.0$	2004.14636
	Bulk RS $g_{KK} \to tt$	1 e, μ	≥ 1 b, ≥ 1J/2j	Yes	36.1	g_{KK} mass 3.8 TeV	$\Gamma/m = 15\%$	1804.10823
	2UED / RPP	1 e, μ	≥ 2 b, ≥ 3 j	Yes	36.1	KK mass 1.8 TeV	Tier (1,1), $\mathcal{B}(A^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2 e, μ	–	–	139	Z' mass 5.1 TeV		1903.06248
	SSM $Z' \to \tau\tau$	2 τ	–	–	36.1	Z' mass 2.42 TeV		1709.07242
	Leptophobic $Z' \to bb$	–	2 b	–	36.1	Z' mass 2.1 TeV		1805.09299
	Leptophobic $Z' \to tt$	0 e, μ	≥ 1 b, ≥ 2 J	Yes	139	Z' mass 4.1 TeV	$\Gamma/m = 1.2\%$	2005.05138
	SSM $W' \to \ell\nu$	1 e, μ	–	Yes	139	W' mass 6.0 TeV		1906.05609
	SSM $W' \to \tau\nu$	1 τ	–	Yes	36.1	W' mass 3.7 TeV		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e, μ	2 j / 1 J	Yes	139	W' mass 4.3 TeV	$g_V = 3$	2004.14636
	HVT $V' \to WV \to qqqq$ model B	0 e, μ	2 J	–	139	V' mass 3.8 TeV	$g_V = 3$	1906.08589
	HVT $V' \to WH/ZH$ model B	multi-channel			36.1	V' mass 2.93 TeV	$g_V = 3$	1712.06518
	HVT $W' \to WH$ model B	0 e, μ	≥ 1 b, ≥ 2 J		139	W' mass 3.2 TeV	$g_V = 3$	CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-channel			36.1	W_R mass 3.25 TeV		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	1 J	–	80	W_R mass 5.0 TeV	$m(N_R) = 0.5$ TeV, $g_L = g_R$	1904.12679
CI	CI $qqqq$	–	2 j	–	37.0	Λ 21.8 TeV	η_{LL}^-	1703.09127
	CI $\ell\ell qq$	2 e, μ	–	–	139	Λ 35.8 TeV	η_{LL}^-	CERN-EP-2020-066
	CI $tttt$	$\geq$1 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	Λ 2.57 TeV	$\lvert C_{4t}\rvert = 4\pi$	1811.02305
DM	Axial-vector mediator (Dirac DM)	0 e, μ	$1 - 4$ j	Yes	36.1	m_{med} 1.55 TeV	g_q=0.25, g_χ=1.0, $m(\chi) = 1$ GeV	1711.03301
	Colored scalar mediator (Dirac DM)	0 e, μ	$1 - 4$ j	Yes	36.1	m_{med} 1.67 TeV	g=1.0, $m(\chi) = 1$ GeV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ	1 J, ≤ 1 j	Yes	3.2	M_* 700 GeV	$m(\chi) < 150$ GeV	1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e, μ	1 b, 0-1 J	Yes	36.1	m_ϕ 3.4 TeV	$y = 0.4$, $\lambda = 0.2$, $m(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e	≥ 2 j	Yes	36.1	LQ mass 1.4 TeV	$\beta = 1$	1902.00377
	Scalar LQ 2nd gen	1,2 μ	≥ 2 j	Yes	36.1	LQ mass 1.56 TeV	$\beta = 1$	1902.00377
	Scalar LQ 3rd gen	2 τ	2 b	–	36.1	LQ_3^u mass 1.03 TeV	$\mathcal{B}(\mathrm{LQ}_3^u \to b\tau) = 1$	1902.08103
	Scalar LQ 3rd gen	0-1 e, μ	2 b	Yes	36.1	LQ_3^d mass 970 GeV	$\mathcal{B}(\mathrm{LQ}_3^d \to t\tau) = 0$	1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-channel			36.1	T mass 1.37 TeV	SU(2) doublet	1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-channel			36.1	B mass 1.34 TeV	SU(2) doublet	1808.02343
	VLQ $T_{5/3}T_{5/3}\lvert T_{5/3} \to Wt + X$	2(SS)/$\geq$3 e,μ	$\geq$1 b, $\geq$1 j	Yes	36.1	$T_{5/3}$ mass 1.64 TeV	$\mathcal{B}(T_{5/3} \to Wt)$= 1, $c(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	≥ 1 b, $\geq$ 1j	Yes	36.1	Y mass 1.85 TeV	$\mathcal{B}(Y \to Wb)$= 1, $c_R(Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ	≥ 1 b, $\geq$ 1j	Yes	79.8	B mass 1.21 TeV	κ_B= 0.5	ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ	≥ 4 j	Yes	20.3	Q mass 690 GeV		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	2 j	–	139	q^* mass 6.7 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	1 j	–	36.7	q^* mass 5.3 TeV	only u^* and d^*, $\Lambda = m(q^*)$	1709.10440
	Excited quark $b^* \to bg$	–	1 b, 1 j	–	36.1	b^* mass 2.6 TeV		1805.09299
	Excited lepton ℓ^*	3 e, μ	–	–	20.3	ℓ^* mass 3.0 TeV	$\Lambda = 3.0$ TeV	1411.2921
	Excited lepton ν^*	3 e, μ, τ	–	–	20.3	ν^* mass 1.6 TeV	$\Lambda = 1.6$ TeV	1411.2921
Other	Type III Seesaw	1 e, μ	≥ 2 j	Yes	79.8	N^0 mass 560 GeV		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	2 j	–	36.1	N_R mass 3.2 TeV	$m(W_R) = 4.1$ TeV, $g_L = g_R$	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS)	–	–	36.1	$H^{\pm\pm}$ mass 870 GeV	DY production	1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	–	–	20.3	$H^{\pm\pm}$ mass 400 GeV	DY production, $\mathcal{B}(H_L^{\pm\pm} \to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–	–	–	36.1	multi-charged particle mass 1.22 TeV	DY production, $\lvert q\rvert = 5e$	1812.03673
	Magnetic monopoles	–	–	–	34.4	monopole mass 2.37 TeV	DY production, $\lvert g\rvert = 1g_D$, spin 1/2	1905.10130

*Only a selection of the available mass limits on new states or phenomena is shown.

†Small-radius (large-radius) jets are denoted by the letter j (J).

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ATLAS Exotics Se

Status: May 2020

ATLAS Preliminary

9) fb^{-1}

$\sqrt{s}$ = 8, 13 TeV

	Model			Reference
Extra dimensions	ADD $G_{KK} + g/q$			1711.03301
	ADD non-resonant $\gamma\gamma$		LO	1707.04147
	ADD QBH			1703.09127
	ADD BH high $\sum p_T$	≥	3 TeV, rot BH	1606.02265
	ADD BH multijet		3 TeV, rot BH	1512.02586
	RS1 $G_{KK} \to \gamma\gamma$			1707.04147
	Bulk RS $G_{KK} \to WW/ZZ$	multi		1808.02380
	Bulk RS $G_{KK} \to WV \to \ell\nu qq$	1		2004.14636
	Bulk RS $g_{KK} \to tt$	1		1804.10823
	2UED / RPP	1	$^{(1,1)} \to tt) = 1$	1803.09678
Gauge bosons	SSM $Z' \to \ell\ell$	2		1903.06248
	SSM $Z' \to \tau\tau$	2		1709.07242
	Leptophobic $Z' \to bb$			1805.09299
	Leptophobic $Z' \to tt$	0		2005.05138
	SSM $W' \to \ell\nu$	1		1906.05609
	SSM $W' \to \tau\nu$	1		1801.06992
	HVT $W' \to WZ \to \ell\nu qq$ model B	1 e		2004.14636
	HVT $V' \to WV \to qqqq$ model B	0 e		1906.08589
	HVT $V' \to WH/ZH$ model B	multi-cl		1712.06518
	HVT $W' \to WH$ model B	0 e		CERN-EP-2020-073
	LRSM $W_R \to tb$	multi-ch		1807.10473
	LRSM $W_R \to \mu N_R$	2 μ	$, g_L = g_R$	1904.12679
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	CI $\ell\ell qq$	2 e,	3 TeV η^-_{LL}	CERN-EP-2020-066
	CI $tttt$	≥1 e		1811.02305
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	Colored scalar mediator (Dirac DM)	0 e,	eV	1711.03301
	$VV\chi\chi$ EFT (Dirac DM)	0 e, μ		1608.02372
	Scalar reson. $\phi \to t\chi$ (Dirac DM)	0-1 e,	$(\chi) = 10$ GeV	1812.09743
LQ	Scalar LQ 1st gen	1,2 e		1902.00377
	Scalar LQ 2nd gen	1,2 μ		1902.00377
	Scalar LQ 3rd gen	2 τ		1902.08103
	Scalar LQ 3rd gen	0-1 e, μ		1902.08103
Heavy quarks	VLQ $TT \to Ht/Zt/Wb + X$	multi-chan		1808.02343
	VLQ $BB \to Wt/Zb + X$	multi-chan		1808.02343
	VLQ $T_{5/3}T_{5/3}\vert T_{5/3} \to Wt + X$	2(SS)/≥3 e	$(T_{5/3}Wt)$= 1	1807.11883
	VLQ $Y \to Wb + X$	1 e, μ	$Wb)$= 1	1812.07343
	VLQ $B \to Hb + X$	0 e,μ, 2 γ		ATLAS-CONF-2018-024
	VLQ $QQ \to WqWq$	1 e, μ		1509.04261
Excited fermions	Excited quark $q^* \to qg$	–	(q^*)	1910.08447
	Excited quark $q^* \to q\gamma$	1 γ	(q^*)	1709.10440
	Excited quark $b^* \to bg$	–		1805.09299
	Excited lepton ℓ^*	3 e, μ		1411.2921
	Excited lepton ν^*	3 e, μ, τ		1411.2921
Other	Type III Seesaw	1 e, μ		ATLAS-CONF-2018-020
	LRSM Majorana ν	2 μ	g_R	1809.11105
	Higgs triplet $H^{\pm\pm} \to \ell\ell$	2,3,4 e, μ (SS		1710.09748
	Higgs triplet $H^{\pm\pm} \to \ell\tau$	3 e, μ, τ	$\to \ell\tau) = 1$	1411.2921
	Multi-charged particles	–		1812.03673
	Magnetic monopoles	–	, spin 1/2	1905.10130

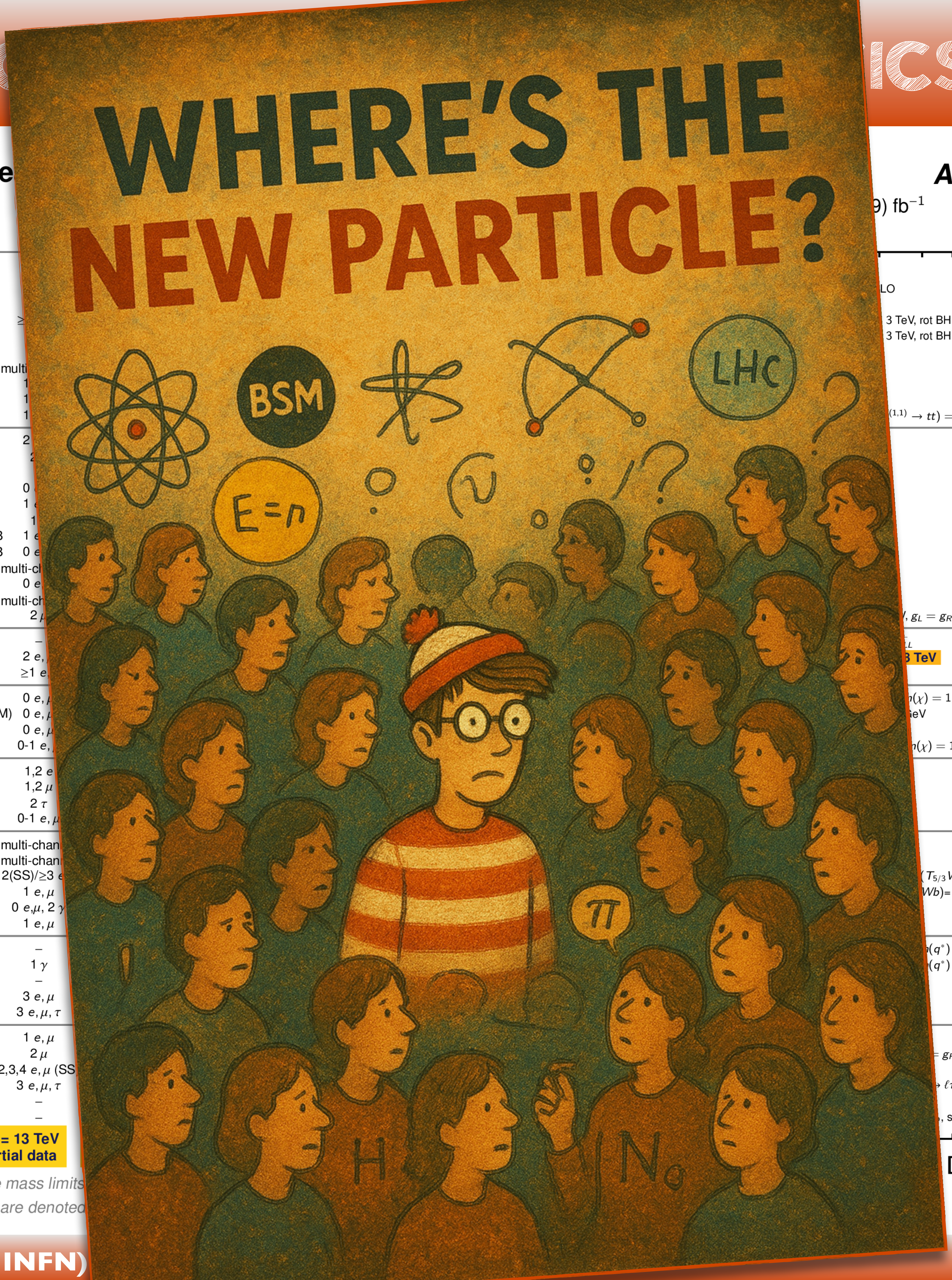
🟩 $\sqrt{s}$ = 8 TeV

🟨 $\sqrt{s}$ = 13 TeV partial data

[TeV]

*Only a selection of the available mass limits

†Small-radius (large-radius) jets are denoted



HEAVY NEW PHYSICS?

NEW PHYSICS SCALE

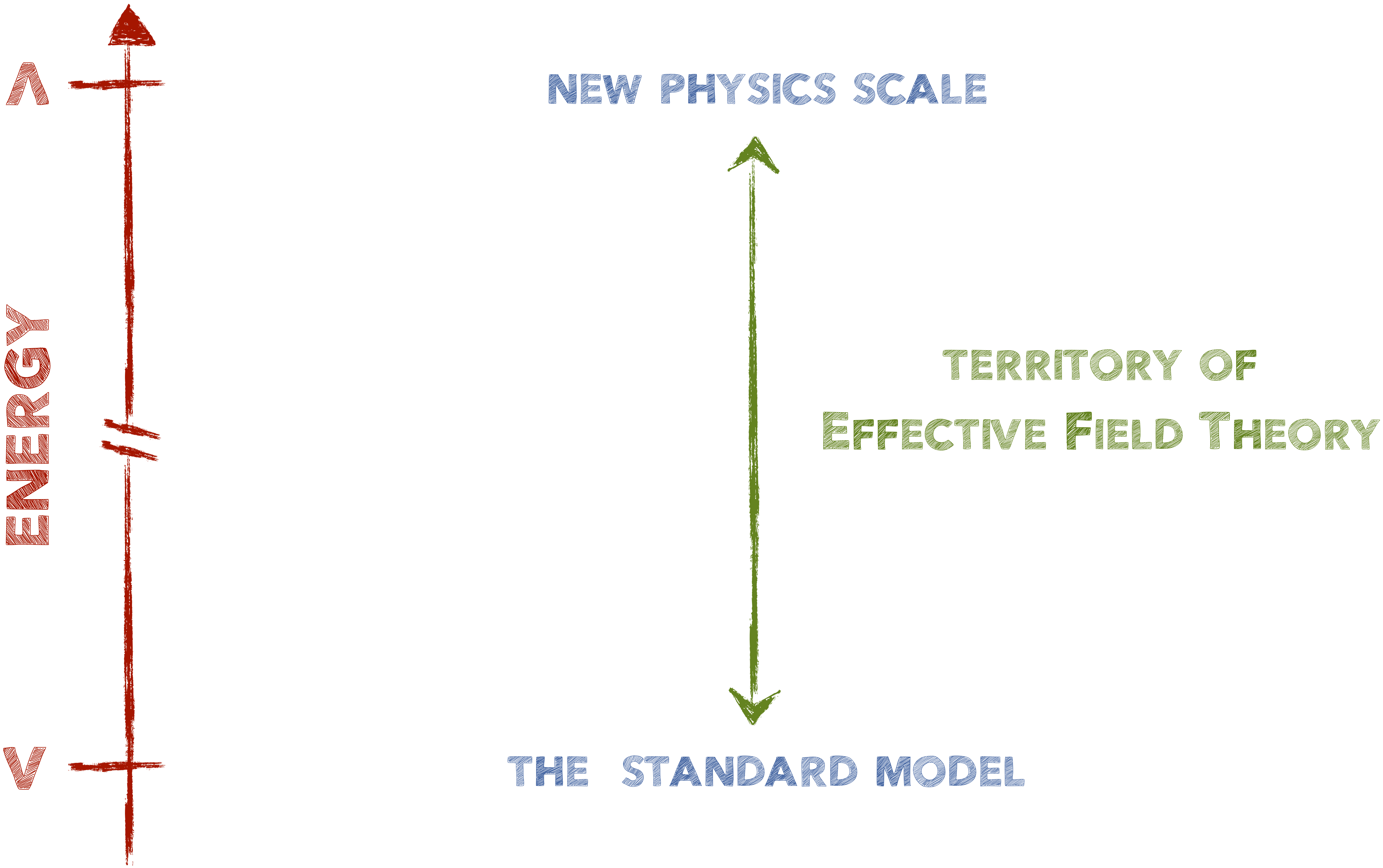
THE STANDARD MODEL

HEAVY NEW PHYSICS?

NEW PHYSICS SCALE

THE STANDARD MODEL

HEAVY NEW PHYSICS?



NEW PHYSICS SCALE

TERRITORY OF
EFFECTIVE FIELD THEORY

THE STANDARD MODEL

SM EFFECTIVE THEORIES

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

SM EFFECTIVE FIELD THEORY

- *Add higher dimensional operators*

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

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

SM EFFECTIVE FIELD THEORY

- *Add higher dimensional operators*

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

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

- $Q_a^{(5)}$ *only 1: Weinberg operator*

— neutrino masses—

SM EFFECTIVE FIELD THEORY

- *Add higher dimensional operators*

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

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- $Q_a^{(5)}$ *only 1: Weinberg operator*

— *neutrino masses* —

- $Q_a^{(6)}$ *59 operators — 2499 parameters* [Buchmuller&Wyler’86, Grzadkowski et al’ 10]

— *most relevant phenomenologically* —

- $Q_a^{(n\geq 7)}$ *just a lot*

— *we neglect them* —

SMEFT DIM-6

- 59 non-redundant operators (× flavor structure)

Warsaw basis [1008.4884]

Operators w/ up to 2 fermions

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger\varphi\, G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu\, \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger\varphi\, \widetilde G_{\mu\nu}^A G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I\, \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger\varphi\, W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r)\widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu\, \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger\varphi\, \widetilde W_{\mu\nu}^I W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r)\tau^I\widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu\, \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger\varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r)\widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu^I\, \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger\varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu\, \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger\tau^I\varphi\, W_{\mu\nu}^I B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i \overleftrightarrow{D}_\mu\, \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde W B}$	$\varphi^\dagger\tau^I\varphi\, \widetilde W_{\mu\nu}^I B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu\varphi)(\bar u_p \gamma^\mu d_r)$

SMEFT DIM-6

- 59 non-redundant operators (× flavor structure)

Warsaw basis [1008.4884]

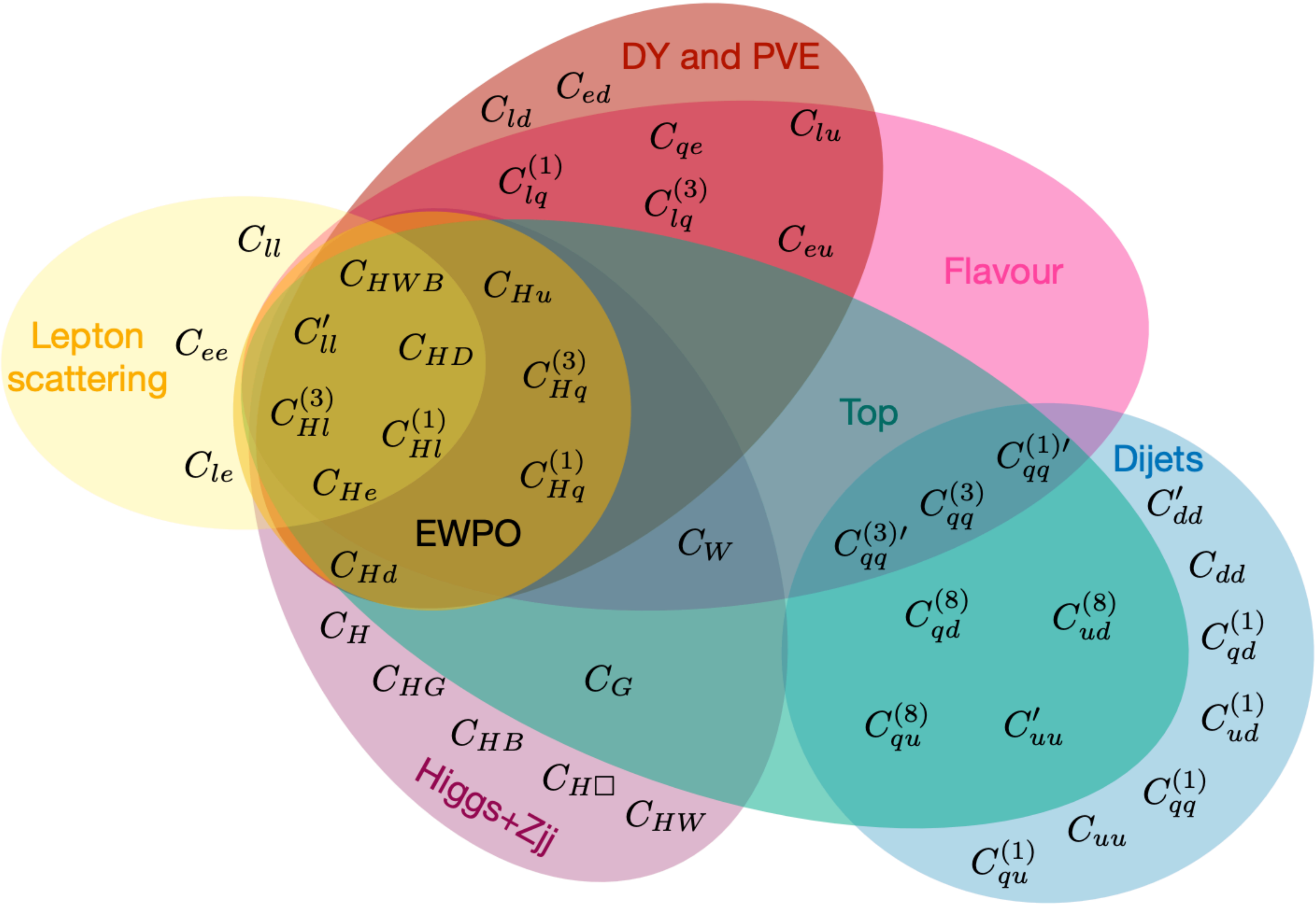
4-fermion operators

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

PROBING DIM-6 OPERATORS

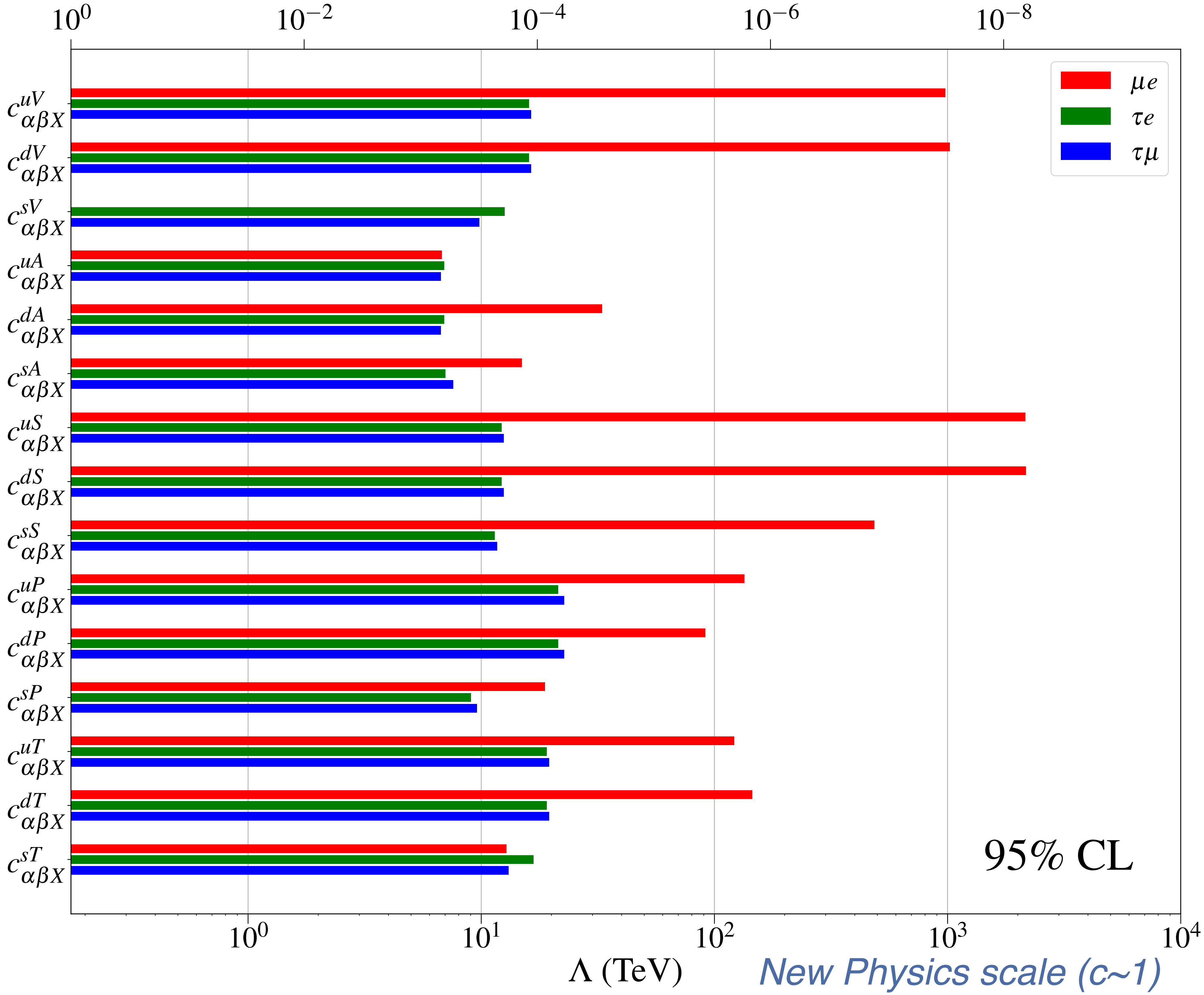
- Rich and complementary phenomenology



— Bartocci, Biekötter, Hurth [2311.04963] —

EXAMPLE: LEPTON FLAVOR VIOLATIONS (LFV)

— Fernández-Martínez, XM, Naredo-Tuero [2403.09772] —



New Physics scale (c~1)

EXAMPLE: LEPTON FLAVOR VIOLATIONS (LFV)

WHAT DO WE REALLY
KNOW FROM THE EFT FRAMEWORK?

cLFV PHYSICS WELL CONSTRAINED

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

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What do we really REALLY know from the EFT framework?

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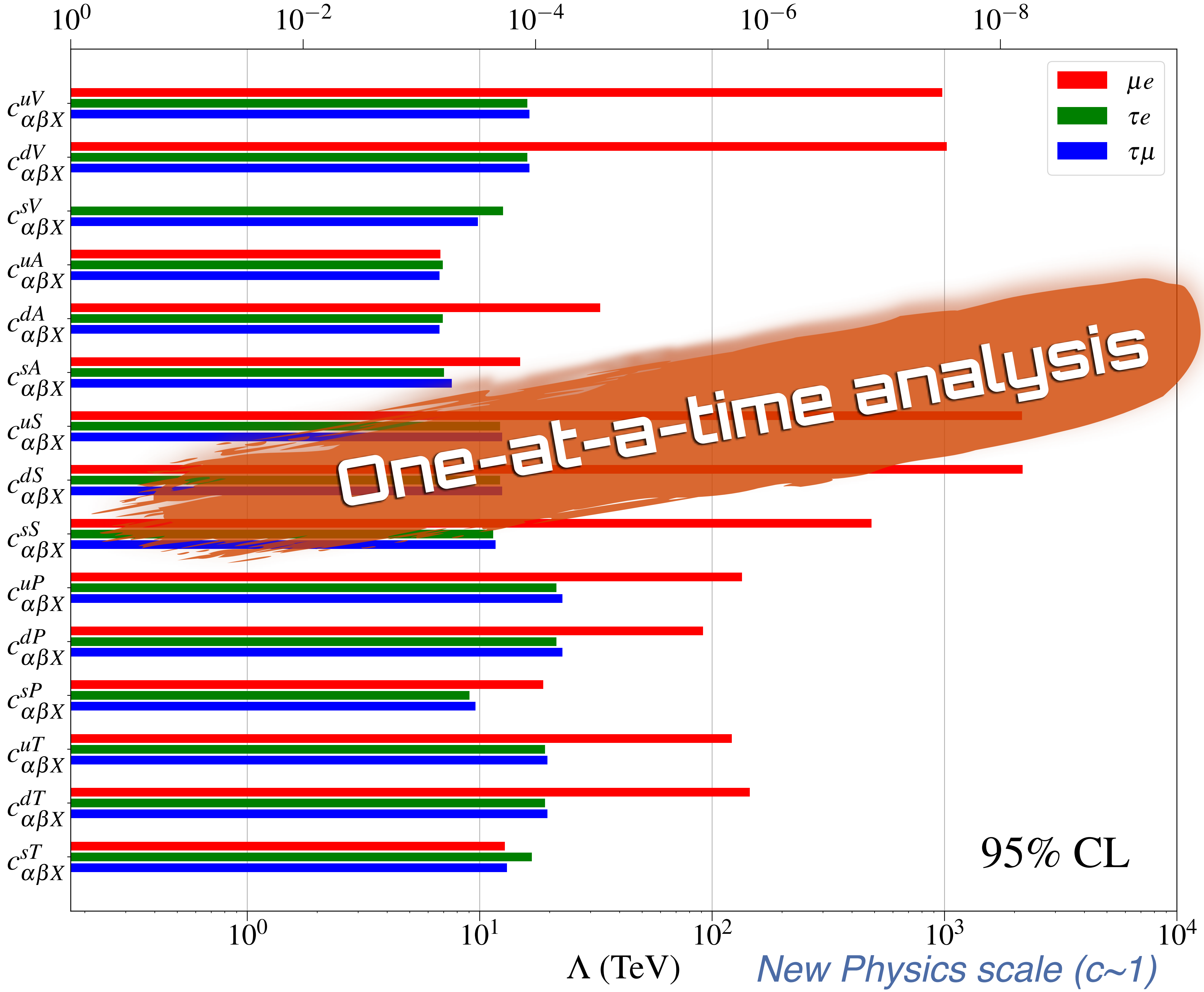


One-at-a-time analysis

New Physics scale (c~1)

— WE NEED TO GO GLOBAL —

— Challenging due to the many new operators —

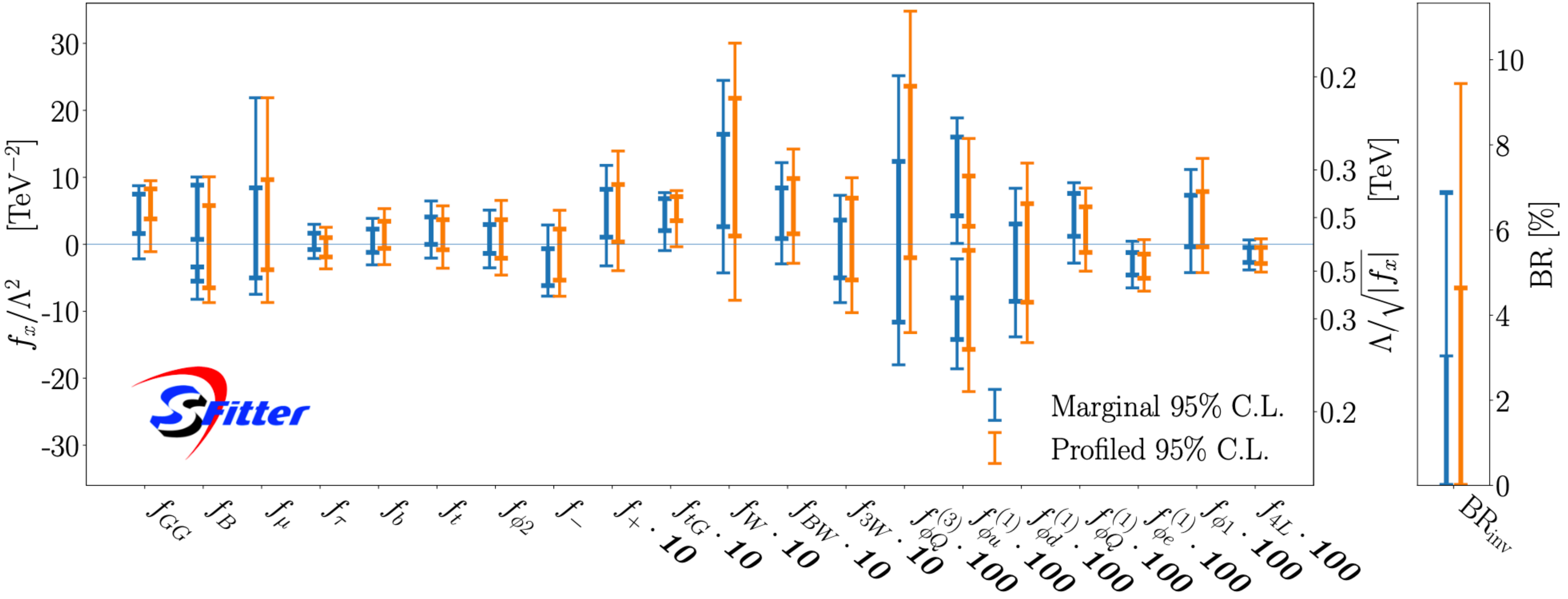
BEFORE GOING TO THE ANALYSES

*We will follow the **model-independent assumption** closely,*
*considering **all (flavor) operators** to be **independent***
*and **without wondering which UV model** could be behind*

EXAMPLE: LHC DATA

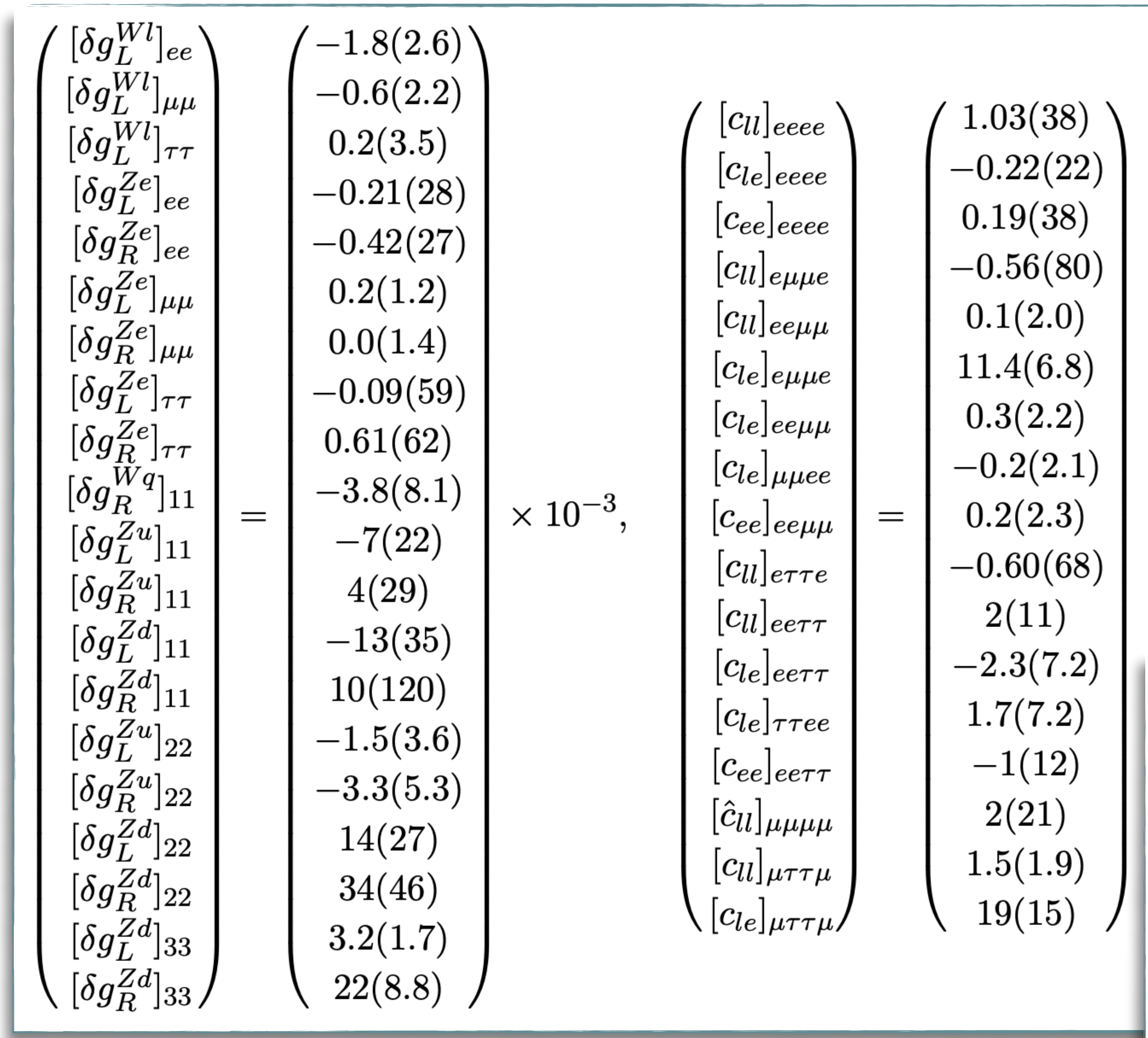
- *Global SMEFT analyses for LHC input*

Brivio et al [2208.08454v3]



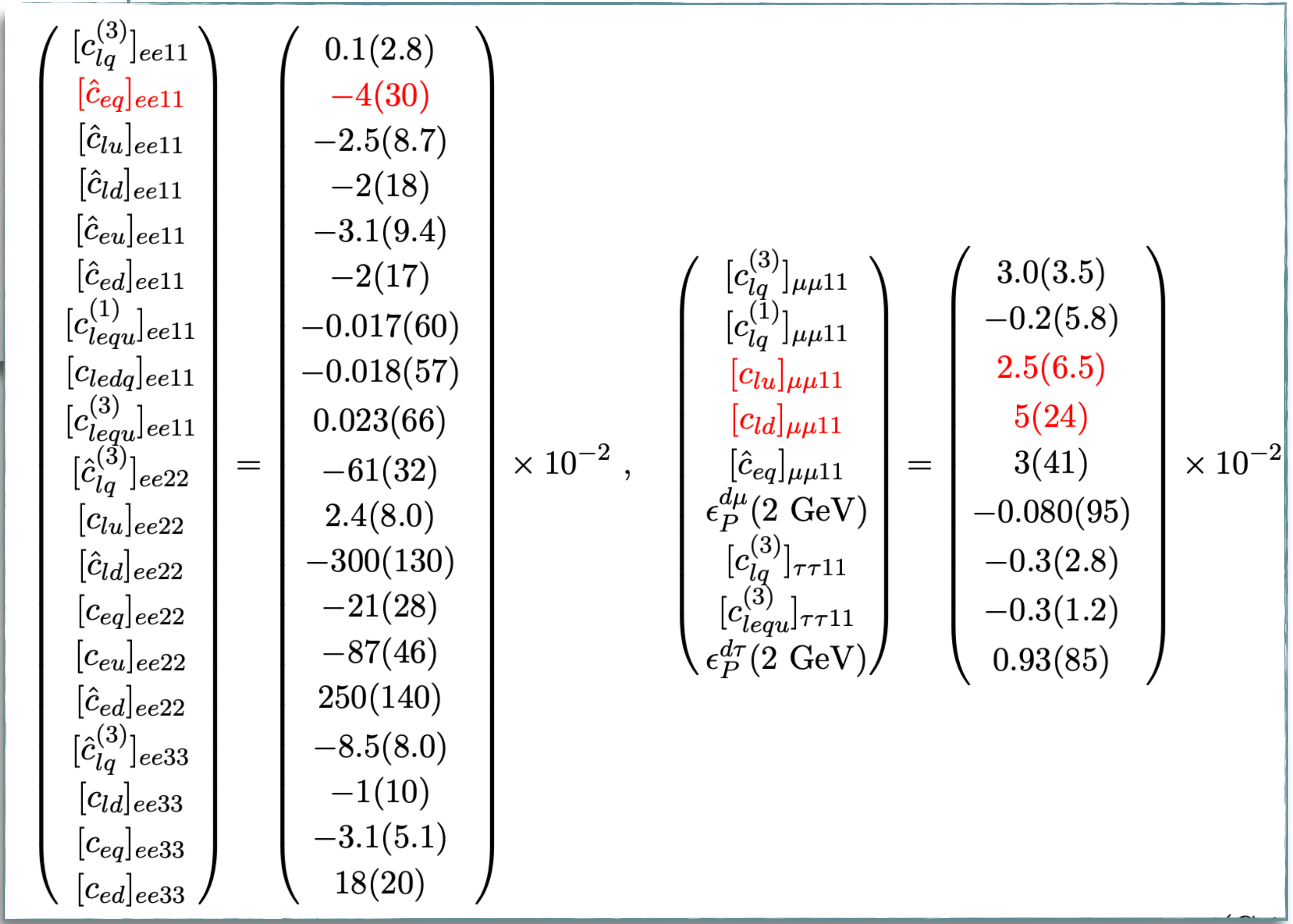
many works Biekötter'18, da Silva Almeida'18, Kraml'19, van Beek'19, Dawson'20, da Silva Almeida'21, Hartland'19, Brivio'19, Ellis'20, Ethier'21, Iranipour'22, Bartocci'23, Kassabov'23….

EXAMPLE: LOW ENERGY PRECISION DATA



$$\begin{pmatrix} [\delta g_L^{Wl}]_{ee} \\ [\delta g_L^{Wl}]_{\mu\mu} \\ [\delta g_L^{Wl}]_{\tau\tau} \\ [\delta g_L^{Ze}]_{ee} \\ [\delta g_R^{Ze}]_{ee} \\ [\delta g_L^{Ze}]_{\mu\mu} \\ [\delta g_R^{Ze}]_{\mu\mu} \\ [\delta g_L^{Ze}]_{\tau\tau} \\ [\delta g_R^{Ze}]_{\tau\tau} \\ [\delta g_R^{Wq}]_{11} \\ [\delta g_L^{Zu}]_{11} \\ [\delta g_R^{Zu}]_{11} \\ [\delta g_L^{Zd}]_{11} \\ [\delta g_R^{Zd}]_{11} \\ [\delta g_L^{Zu}]_{22} \\ [\delta g_R^{Zu}]_{22} \\ [\delta g_L^{Zd}]_{22} \\ [\delta g_R^{Zd}]_{22} \\ [\delta g_L^{Zd}]_{33} \\ [\delta g_R^{Zd}]_{33} \end{pmatrix} = \begin{pmatrix} -1.8(2.6) \\ -0.6(2.2) \\ 0.2(3.5) \\ -0.21(28) \\ -0.42(27) \\ 0.2(1.2) \\ 0.0(1.4) \\ -0.09(59) \\ 0.61(62) \\ -3.8(8.1) \\ -7(22) \\ 4(29) \\ -13(35) \\ 10(120) \\ -1.5(3.6) \\ -3.3(5.3) \\ 14(27) \\ 34(46) \\ 3.2(1.7) \\ 22(8.8) \end{pmatrix} \times 10^{-3}, \qquad \begin{pmatrix} [c_{ll}]_{eeee} \\ [c_{le}]_{eeee} \\ [c_{ee}]_{eeee} \\ [c_{ll}]_{e\mu\mu e} \\ [c_{ll}]_{ee\mu\mu} \\ [c_{le}]_{e\mu\mu e} \\ [c_{le}]_{ee\mu\mu} \\ [c_{le}]_{\mu\mu ee} \\ [c_{ee}]_{ee\mu\mu} \\ [c_{ll}]_{e\tau\tau e} \\ [c_{ll}]_{ee\tau\tau} \\ [c_{le}]_{ee\tau\tau} \\ [c_{le}]_{\tau\tau ee} \\ [c_{ee}]_{ee\tau\tau} \\ [\hat{c}_{ll}]_{\mu\mu\mu\mu} \\ [c_{ll}]_{\mu\tau\tau\mu} \\ [c_{le}]_{\mu\tau\tau\mu} \end{pmatrix} = \begin{pmatrix} 1.03(38) \\ -0.22(22) \\ 0.19(38) \\ -0.56(80) \\ 0.1(2.0) \\ 11.4(6.8) \\ 0.3(2.2) \\ -0.2(2.1) \\ 0.2(2.3) \\ -0.60(68) \\ 2(11) \\ -2.3(7.2) \\ 1.7(7.2) \\ -1(12) \\ 2(21) \\ 1.5(1.9) \\ 19(15) \end{pmatrix} \times 10^{-2},$$

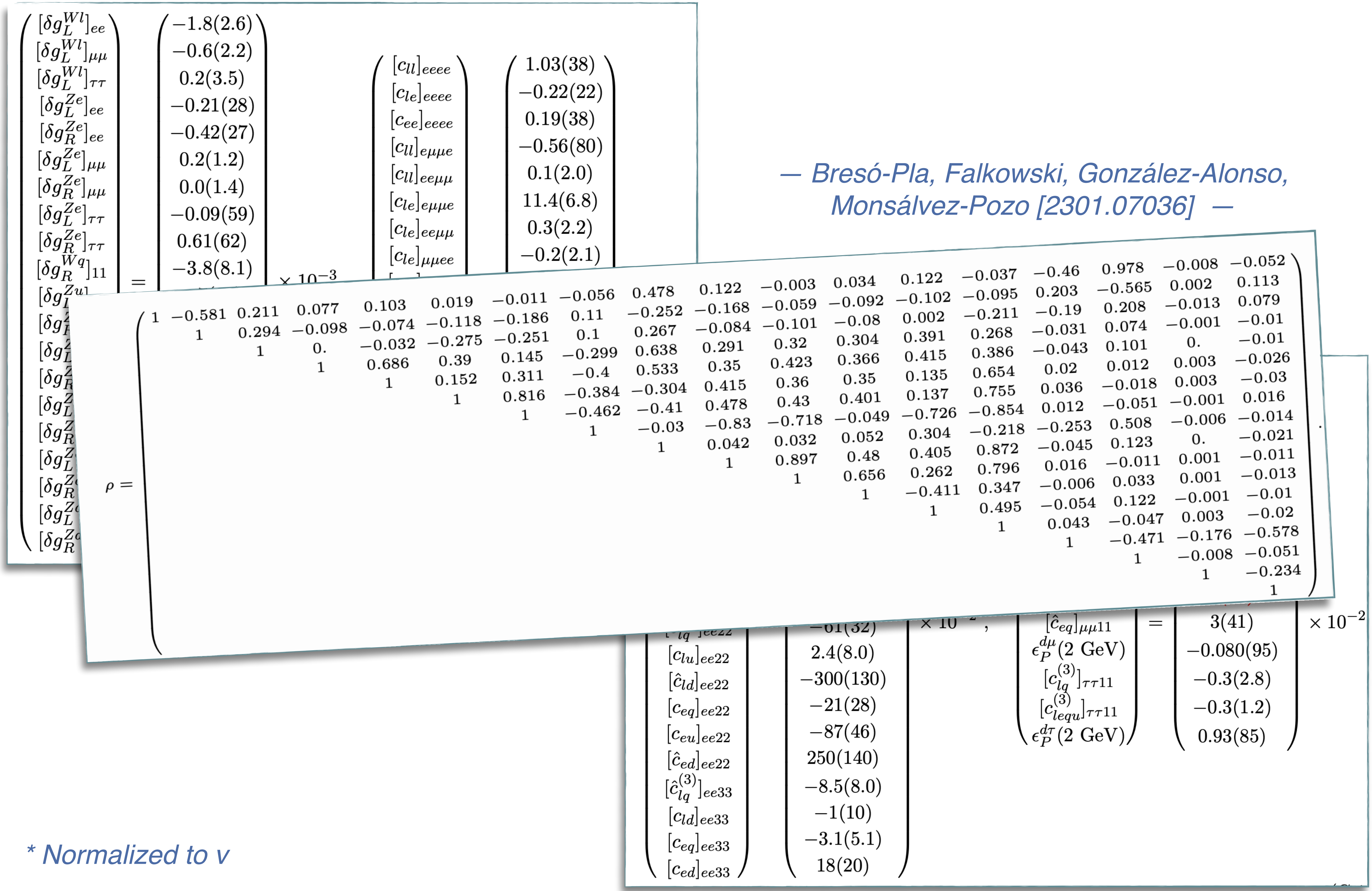
— Bresó-Pla, Falkowski, González-Alonso, Monsálvez-Pozo [2301.07036] —



$$\begin{pmatrix} [c_{lq}^{(3)}]_{ee11} \\ [\hat{c}_{eq}]_{ee11} \\ [\hat{c}_{lu}]_{ee11} \\ [\hat{c}_{ld}]_{ee11} \\ [\hat{c}_{eu}]_{ee11} \\ [\hat{c}_{ed}]_{ee11} \\ [c_{lequ}^{(1)}]_{ee11} \\ [c_{ledq}]_{ee11} \\ [c_{lequ}^{(3)}]_{ee11} \\ [\hat{c}_{lq}^{(3)}]_{ee22} \\ [c_{lu}]_{ee22} \\ [\hat{c}_{ld}]_{ee22} \\ [c_{eq}]_{ee22} \\ [c_{eu}]_{ee22} \\ [\hat{c}_{ed}]_{ee22} \\ [\hat{c}_{lq}^{(3)}]_{ee33} \\ [c_{ld}]_{ee33} \\ [c_{eq}]_{ee33} \\ [c_{ed}]_{ee33} \end{pmatrix} = \begin{pmatrix} 0.1(2.8) \\ -4(30) \\ -2.5(8.7) \\ -2(18) \\ -3.1(9.4) \\ -2(17) \\ -0.017(60) \\ -0.018(57) \\ 0.023(66) \\ -61(32) \\ 2.4(8.0) \\ -300(130) \\ -21(28) \\ -87(46) \\ 250(140) \\ -8.5(8.0) \\ -1(10) \\ -3.1(5.1) \\ 18(20) \end{pmatrix} \times 10^{-2}\,, \qquad \begin{pmatrix} [c_{lq}^{(3)}]_{\mu\mu 11} \\ [c_{lq}^{(1)}]_{\mu\mu 11} \\ [c_{lu}]_{\mu\mu 11} \\ [c_{ld}]_{\mu\mu 11} \\ [\hat{c}_{eq}]_{\mu\mu 11} \\ \epsilon_P^{d\mu}(2\text{ GeV}) \\ [c_{lq}^{(3)}]_{\tau\tau 11} \\ [c_{lequ}^{(3)}]_{\tau\tau 11} \\ \epsilon_P^{d\tau}(2\text{ GeV}) \end{pmatrix} = \begin{pmatrix} 3.0(3.5) \\ -0.2(5.8) \\ 2.5(6.5) \\ 5(24) \\ 3(41) \\ -0.080(95) \\ -0.3(2.8) \\ -0.3(1.2) \\ 0.93(85) \end{pmatrix} \times 10^{-2}$$

** Normalized to v*

EXAMPLE: LOW ENERGY PRECISION DATA



$$\begin{pmatrix} [\delta g_L^{Wl}]_{ee} \\ [\delta g_L^{Wl}]_{\mu\mu} \\ [\delta g_L^{Wl}]_{\tau\tau} \\ [\delta g_L^{Ze}]_{ee} \\ [\delta g_R^{Ze}]_{ee} \\ [\delta g_L^{Ze}]_{\mu\mu} \\ [\delta g_R^{Ze}]_{\mu\mu} \\ [\delta g_L^{Ze}]_{\tau\tau} \\ [\delta g_R^{Ze}]_{\tau\tau} \\ [\delta g_R^{Wq}]_{11} \end{pmatrix} = \begin{pmatrix} -1.8(2.6) \\ -0.6(2.2) \\ 0.2(3.5) \\ -0.21(28) \\ -0.42(27) \\ 0.2(1.2) \\ 0.0(1.4) \\ -0.09(59) \\ 0.61(62) \\ -3.8(8.1) \end{pmatrix} \times 10^{-3}$$

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— Bresó-Pla, Falkowski, González-Alonso, Monsálvez-Pozo [2301.07036] —

$$\rho = \begin{pmatrix}
1 & -0.581 & 0.211 & 0.077 & 0.103 & 0.019 & -0.011 & -0.056 & 0.478 & 0.122 & -0.003 & 0.034 & 0.122 & -0.037 & -0.46 & 0.978 & -0.008 & -0.052 \\
 & 1 & 0.294 & -0.098 & -0.074 & -0.118 & -0.186 & 0.11 & -0.252 & -0.168 & -0.059 & -0.092 & -0.102 & -0.095 & 0.203 & -0.565 & 0.002 & 0.113 \\
 & & 1 & 0. & -0.032 & -0.275 & -0.251 & 0.1 & 0.267 & -0.084 & -0.101 & -0.08 & 0.002 & -0.211 & -0.19 & 0.208 & -0.013 & 0.079 \\
 & & & 1 & 0.686 & 0.39 & 0.145 & -0.299 & 0.638 & 0.291 & 0.32 & 0.304 & 0.391 & 0.268 & -0.031 & 0.074 & -0.001 & -0.01 \\
 & & & & 1 & 0.152 & 0.311 & -0.4 & 0.533 & 0.35 & 0.423 & 0.366 & 0.415 & 0.386 & -0.043 & 0.101 & 0. & -0.01 \\
 & & & & & 1 & 0.816 & -0.384 & -0.304 & 0.415 & 0.36 & 0.35 & 0.135 & 0.654 & 0.02 & 0.012 & 0.003 & -0.026 \\
 & & & & & & 1 & -0.462 & -0.41 & 0.478 & 0.43 & 0.401 & 0.137 & 0.755 & 0.036 & -0.018 & 0.003 & -0.03 \\
 & & & & & & & 1 & -0.03 & -0.83 & -0.718 & -0.049 & -0.726 & -0.854 & 0.012 & -0.051 & -0.001 & 0.016 \\
 & & & & & & & & 1 & 0.042 & 0.032 & 0.052 & 0.304 & -0.218 & -0.253 & 0.508 & -0.006 & -0.014 \\
 & & & & & & & & & 1 & 0.897 & 0.48 & 0.405 & 0.872 & -0.045 & 0.123 & 0. & -0.021 \\
 & & & & & & & & & & 1 & 0.656 & 0.262 & 0.796 & 0.016 & -0.011 & 0.001 & -0.011 \\
 & & & & & & & & & & & 1 & -0.411 & 0.347 & -0.006 & 0.033 & 0.001 & -0.013 \\
 & & & & & & & & & & & & 1 & 0.495 & -0.054 & 0.122 & -0.001 & -0.01 \\
 & & & & & & & & & & & & & 1 & 0.043 & -0.047 & 0.003 & -0.02 \\
 & & & & & & & & & & & & & & 1 & -0.471 & -0.176 & -0.578 \\
 & & & & & & & & & & & & & & & 1 & -0.008 & -0.051 \\
 & & & & & & & & & & & & & & & & 1 & -0.234 \\
 & & & & & & & & & & & & & & & & & 1
\end{pmatrix}.$$

$$\begin{pmatrix} [c_{lu}]_{ee22} \\ [\hat{c}_{ld}]_{ee22} \\ [c_{eq}]_{ee22} \\ [c_{eu}]_{ee22} \\ [\hat{c}_{ed}]_{ee22} \\ [\hat{c}_{lq}^{(3)}]_{ee33} \\ [c_{ld}]_{ee33} \\ [c_{eq}]_{ee33} \\ [c_{ed}]_{ee33} \end{pmatrix} \quad \begin{pmatrix} 2.4(8.0) \\ -300(130) \\ -21(28) \\ -87(46) \\ 250(140) \\ -8.5(8.0) \\ -1(10) \\ -3.1(5.1) \\ 18(20) \end{pmatrix}$$

$$\begin{pmatrix} [\hat{c}_{eq}]_{\mu\mu11} \\ \epsilon_P^{d\mu}(2\ \mathrm{GeV}) \\ [c_{lq}^{(3)}]_{\tau\tau11} \\ [c_{lequ}^{(3)}]_{\tau\tau11} \\ \epsilon_P^{d\tau}(2\ \mathrm{GeV}) \end{pmatrix} = \begin{pmatrix} 3(41) \\ -0.080(95) \\ -0.3(2.8) \\ -0.3(1.2) \\ 0.93(85) \end{pmatrix} \times 10^{-2}$$

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STATUS OF SMEFT ANALYSES

— Broadly speaking, we found two main strategies —

- *Linearized global analyses*
  - *Keep only leading terms: interference w/ SM*
  - *Linear ➠ Gaussean likelihood ➠ Analytically treatable*
  - *Easy to identify flat/poorly constrained directions*

- *One-at-a-time analyses*
  - *When there is no interference w/ SM (e.g. LFV)*
  - *No fully global analyses available*

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CAN WE IMPROVE IT?

OUTLINE

- *SM Effective Field Theories*

— Focus on leptonic operators —

- *Neutrino Non Standard Interactions*

— popular neutrino-EFT interactions —

- *Global analysis of LFC fermionic operators*

— Can we improve current status using neutrino data? —

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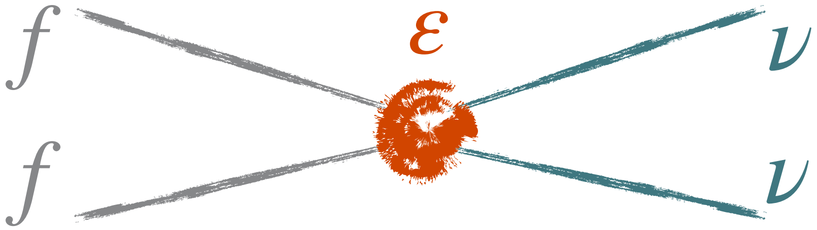
NON STANDARD INTERACTIONS (NSI)

— Wolfenstein'78, Mikheyev and Smirnov'85, Roulet'91, Guzzo et al'91, Grossman'95, Gonzalez-García et al.'99, … —

- *New EFT interactions modifying neutrino production, propagation and scattering*



$$\mathcal{L}_{\text{NC-NSI}} \supset -2\sqrt{2}G_F\varepsilon^{f,X}_{\alpha\beta}(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta)(\bar{f}\gamma^\mu P_X f)\,,$$

$$\begin{aligned}\mathcal{L}_{\text{CC-NSI}} \supset -2\sqrt{2}G_F\Big\{&\varepsilon^{\mu eX}_{\alpha\beta}(\bar{\nu}_\alpha\gamma_\mu P_L\nu_\beta)(\bar{\mu}\gamma^\mu P_X e) + \varepsilon^{udL}_{\alpha\beta}(\bar{e}_\alpha\gamma_\mu P_L\nu_\beta)(\bar{u}\gamma^\mu P_L d)\\ &+\varepsilon^{udR}_{\alpha\beta}(\bar{e}_\alpha\gamma_\mu P_L\nu_\beta)(\bar{u}\gamma^\mu P_R d) + \tfrac{1}{2}\varepsilon^{udS}_{\alpha\beta}(\bar{e}_\alpha P_L\nu_\beta)(\bar{u}d)\\ &+\tfrac{1}{2}\varepsilon^{udP}_{\alpha\beta}(\bar{e}_\alpha P_L\nu_\beta)(\bar{u}\gamma_5 d) + \varepsilon^{udT}_{\alpha\beta}(\bar{e}_\alpha\sigma_{\mu\nu}P_L\nu_\beta)(\bar{u}\sigma^{\mu\nu}P_L d)\Big\} + h.c.\end{aligned}$$

- *Deeply studied and searched for in neutrino oscillations*

— e.g. review Farzan and Tortola, Front. in Phys. 6 (2018) 10, [arXiv:1710.09360] —

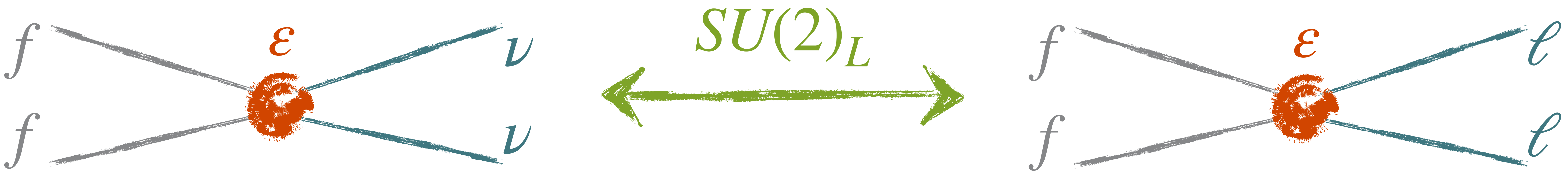
— although **caution is needed with normalization** Coloma et al [arXiv:2411.00090] —

NON STANDARD INTERACTIONS (NSI)

NSI

ARE NOT GAUGE INVARIANT!

NON STANDARD INTERACTIONS (NSI)

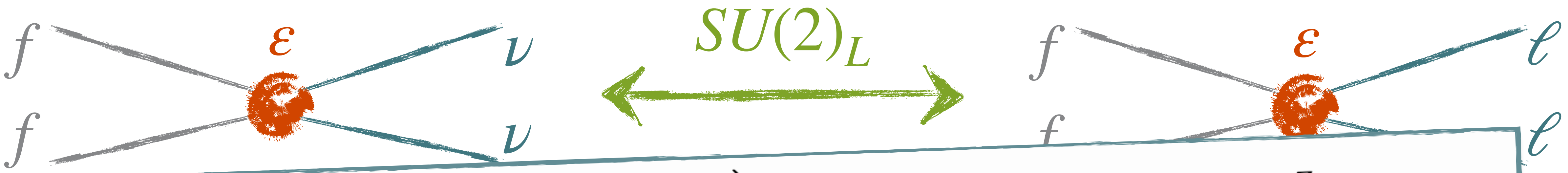


- *NSI ⊃ SMEFT*

— well studied matching —

— Gavela et al.’08, Falkowski et al.’17, Jenkins et al.’18, Bischer et al.’19, Cherchiglia et al’23,… —

NON STANDARD INTERACTIONS (NSI)



$$\varepsilon^{e,V}_{\alpha\alpha} = \delta_{e\alpha}\left(\delta g_L^{We} - \delta g_L^{W\mu} + \frac{1}{2}[c_{\ell\ell}]_{e\mu\mu e}\right) - (1-4s_{\rm w}^2)\delta g_L^{Z\nu_\alpha} + \delta g_L^{Ze} + \delta g_R^{Ze}$$

$$- \frac{1}{2}\left([c_{\ell\ell}]_{ee\alpha\alpha} + [c_{\ell e}]_{\alpha\alpha ee}\right),$$

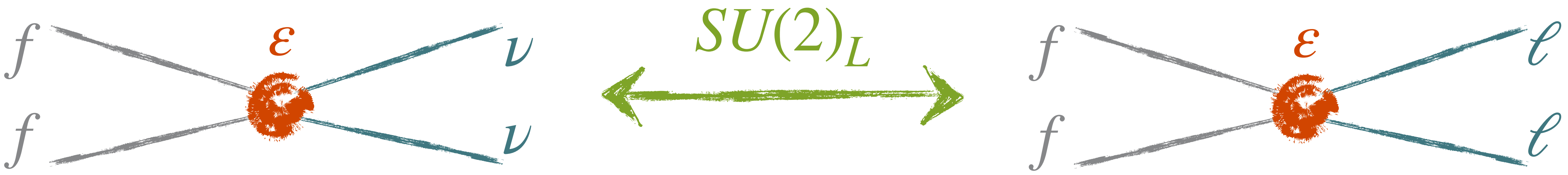
$$\varepsilon^{u,V}_{\alpha\alpha} = \delta g_L^{Zu} + \delta g_R^{Zu} + \left(1 - \frac{8}{3}s_{\rm w}^2\right)\delta g^{Z\nu_\alpha} - \frac{1}{2}\left([c_{\ell q}^{(1)}]_{\alpha\alpha 11} + [c_{\ell q}^{(3)}]_{\alpha\alpha 11} + [c_{\ell u}]_{\alpha\alpha 11}\right),$$

$$\varepsilon^{d,V}_{\alpha\alpha} = \delta g_L^{Zd} + \delta g_R^{Zd} - \left(1 - \frac{4}{3}s_{\rm w}^2\right)\delta g^{Z\nu_\alpha} - \frac{1}{2}\left([c_{\ell q}^{(1)}]_{\alpha\alpha 11} - [c_{\ell q}^{(3)}]_{\alpha\alpha 11} + [c_{\ell d}]_{\alpha\alpha 11}\right),$$

$$\varepsilon^{u,A}_{\alpha\alpha} = \delta g_L^{Zu} - \delta g_R^{Zu} + \delta g^{Z\nu_\alpha} - \frac{1}{2}\left([c_{\ell q}^{(1)}]_{\alpha\alpha 11} + [c_{\ell q}^{(3)}]_{\alpha\alpha 11} - [c_{\ell u}]_{\alpha\alpha 11}\right),$$

$$\varepsilon^{d,A}_{\alpha\alpha} = \delta g_L^{Zd} - \delta g_R^{Zd} - \delta g^{Z\nu_\alpha} - \frac{1}{2}\left([c_{\ell q}^{(1)}]_{\alpha\alpha 11} - [c_{\ell q}^{(3)}]_{\alpha\alpha 11} - [c_{\ell d}]_{\alpha\alpha 11}\right),$$

NON STANDARD INTERACTIONS (NSI)



- *NSI ⊃ SMEFT*

— well studied matching —

— Gavela et al.'08, Falkowski et al.'17, Jenkins et al.'18, Bischer et al.'19, Cherchiglia et al'23,… —

- *Charged lepton processes give much stronger bounds than neutrinos*

— Gavela et al [arXiv:0809.3451], Antusch et al [arXiv:0807.1003] —

CAN NEUTRINOS HELP PROBING THE SM EFFECTIVE THEORY?

NEUTRINO DATA IRRELEVANT

— compared to charged leptons —

CAN NEUTRINOS HELP PROBING THE SM EFFECTIVE THEORY?

— one-at-a-time —

NEUTRINO DATA IRRELEVANT

— compared to charged leptons —

CAN NEUTRINOS HELP PROBING THE SM EFFECTIVE THEORY?

— one-at-a-time —

NEUTRINO DATA IRRELEVANT

— compared to charged leptons —

— Global Picture —

???

— PART III —

GLOBAL ANALYSIS OF LFC OPERATORS

arXiv: 2411.00090

Improving the global SMEFT picture with bounds on neutrino NSI

Pilar Coloma, Enrique Fernández-Martínez, Jacobo López-Pavón, XM,
Daniel Naredo-Tuero *and Salvador Urrea*

GLOBAL ANALYSES TO PRECISION DATA

Falkowski, González-Alonso et al *explored it in great detail*

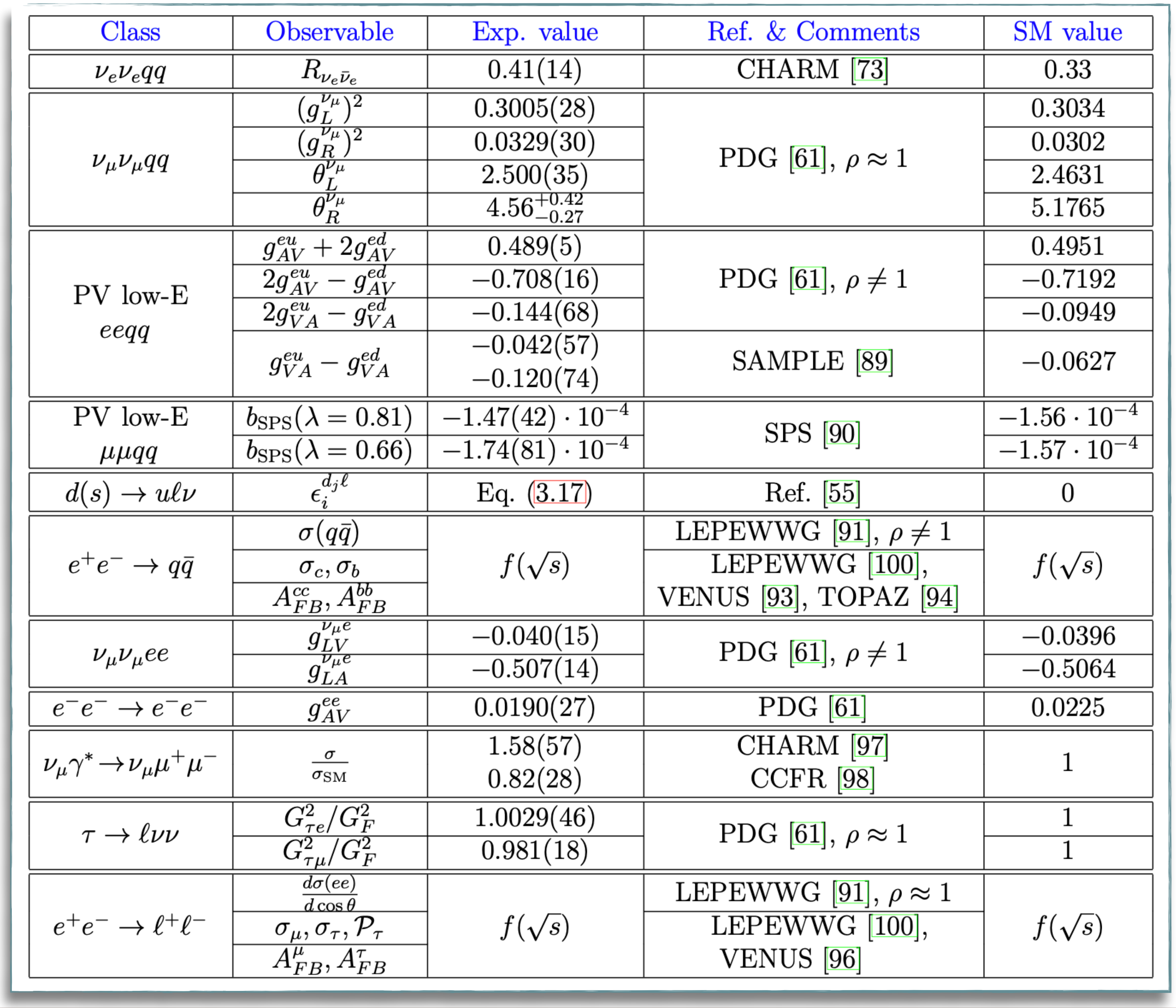
— M. Gonzalez-Alonso et al.'15, Falkowski et al.'17, Bresó-Pla et al.'23… —

GLOBAL ANALYSES TO PRECISION DATA

***Falkowski, González-Alonso et al** explored it in great detail*

— M. Gonzalez-Alonso et al.’15, Falkowski et al.’17, Bresó-Pla et al.’23… —

- *Collected an extensive list of precision observables*



Class	Observable	Exp. value	Ref. & Comments	SM value
$\nu_e\nu_e qq$	$R_{\nu_e\bar{\nu}_e}$	0.41(14)	CHARM [73]	0.33
$\nu_\mu\nu_\mu qq$	$(g_L^{\nu_\mu})^2$	0.3005(28)	PDG [61], $\rho \approx 1$	0.3034
	$(g_R^{\nu_\mu})^2$	0.0329(30)		0.0302
	$\theta_L^{\nu_\mu}$	2.500(35)		2.4631
	$\theta_R^{\nu_\mu}$	$4.56^{+0.42}_{-0.27}$		5.1765
PV low-E $eeqq$	$g_{AV}^{eu} + 2g_{AV}^{ed}$	0.489(5)	PDG [61], $\rho \neq 1$	0.4951
	$2g_{AV}^{eu} - g_{AV}^{ed}$	−0.708(16)		−0.7192
	$2g_{VA}^{eu} - g_{VA}^{ed}$	−0.144(68)		−0.0949
	$g_{VA}^{eu} - g_{VA}^{ed}$	−0.042(57) −0.120(74)	SAMPLE [89]	−0.0627
PV low-E $\mu\mu qq$	$b_{\rm SPS}(\lambda = 0.81)$	$-1.47(42) \cdot 10^{-4}$	SPS [90]	$-1.56 \cdot 10^{-4}$
	$b_{\rm SPS}(\lambda = 0.66)$	$-1.74(81) \cdot 10^{-4}$		$-1.57 \cdot 10^{-4}$
$d(s) \to u\ell\nu$	$\epsilon_i^{d_j\ell}$	Eq. (3.17)	Ref. [55]	0
$e^+e^- \to q\bar{q}$	$\sigma(q\bar{q})$	$f(\sqrt{s})$	LEPEWWG [91], $\rho \neq 1$	$f(\sqrt{s})$
	σ_c, σ_b		LEPEWWG [100], VENUS [93], TOPAZ [94]	
	A_{FB}^{cc}, A_{FB}^{bb}			
$\nu_\mu\nu_\mu ee$	$g_{LV}^{\nu_\mu e}$	−0.040(15)	PDG [61], $\rho \neq 1$	−0.0396
	$g_{LA}^{\nu_\mu e}$	−0.507(14)		−0.5064
$e^-e^- \to e^-e^-$	g_{AV}^{ee}	0.0190(27)	PDG [61]	0.0225
$\nu_\mu\gamma^* \to \nu_\mu\mu^+\mu^-$	$\frac{\sigma}{\sigma_{\rm SM}}$	1.58(57) 0.82(28)	CHARM [97] CCFR [98]	1
$\tau \to \ell\nu\nu$	$G_{\tau e}^2/G_F^2$	1.0029(46)	PDG [61], $\rho \approx 1$	1
	$G_{\tau\mu}^2/G_F^2$	0.981(18)		1
$e^+e^- \to \ell^+\ell^-$	$\frac{d\sigma(ee)}{d\cos\theta}$	$f(\sqrt{s})$	LEPEWWG [91], $\rho \approx 1$	$f(\sqrt{s})$
	$\sigma_\mu, \sigma_\tau, \mathcal{P}_\tau$		LEPEWWG [100], VENUS [96]	
	A_{FB}^μ, A_{FB}^τ			

Falkowski et al. [1706.03783]

+ Pole observables
(see Efrati et al. [1503.07872])

GLOBAL ANALYSES TO PRECISION DATA

Falkowski, González-Alonso et al *explored it in great detail*

— M. Gonzalez-Alonso et al.'15, Falkowski et al.'17, Bresó-Pla et al.'23… —

- *Collected an extensive list of precision observables*
- *Worked at linear order*

— keep only interference w/ SM —
— Gaussian likelihood for WCs —

- *Constraint 65 combinations of WCs*
- *Built 65x65 correlation matrices*

GLOBAL ANALYSES TO PRECISION DATA

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- *Worked at linear order*

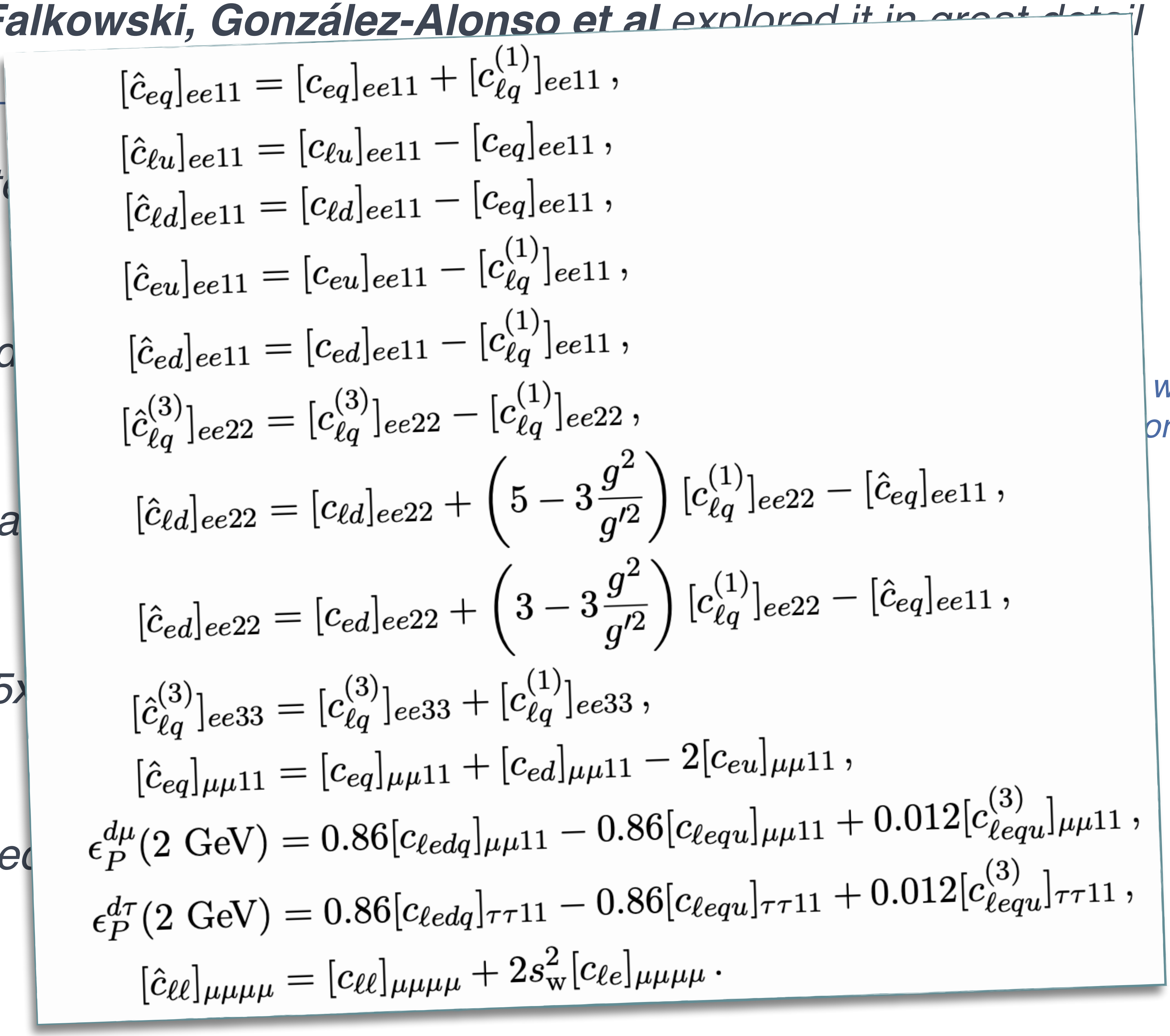
— keep only interference w/ SM —
— Gaussian likelihood for WCs —

- *Constraint 65 combinations of WCs*
- *Built 65x65 correlation matrices*
- *Identified and isolated 13 flat (or poorly constraint) directions*

GLOBAL ANALYSES TO PRECISION DATA

Falkowski, González-Alonso et al *explored it in great detail*

- *Collect*
- *Worked*
- *Constra*
- *Built 65x*
- *Identified*



$$
\begin{aligned}
[\hat{c}_{eq}]_{ee11} &= [c_{eq}]_{ee11} + [c^{(1)}_{\ell q}]_{ee11}\,, \\
[\hat{c}_{\ell u}]_{ee11} &= [c_{\ell u}]_{ee11} - [c_{eq}]_{ee11}\,, \\
[\hat{c}_{\ell d}]_{ee11} &= [c_{\ell d}]_{ee11} - [c_{eq}]_{ee11}\,, \\
[\hat{c}_{eu}]_{ee11} &= [c_{eu}]_{ee11} - [c^{(1)}_{\ell q}]_{ee11}\,, \\
[\hat{c}_{ed}]_{ee11} &= [c_{ed}]_{ee11} - [c^{(1)}_{\ell q}]_{ee11}\,, \\
[\hat{c}^{(3)}_{\ell q}]_{ee22} &= [c^{(3)}_{\ell q}]_{ee22} - [c^{(1)}_{\ell q}]_{ee22}\,, \\
[\hat{c}_{\ell d}]_{ee22} &= [c_{\ell d}]_{ee22} + \left(5 - 3\frac{g^2}{g'^2}\right)[c^{(1)}_{\ell q}]_{ee22} - [\hat{c}_{eq}]_{ee11}\,, \\
[\hat{c}_{ed}]_{ee22} &= [c_{ed}]_{ee22} + \left(3 - 3\frac{g^2}{g'^2}\right)[c^{(1)}_{\ell q}]_{ee22} - [\hat{c}_{eq}]_{ee11}\,, \\
[\hat{c}^{(3)}_{\ell q}]_{ee33} &= [c^{(3)}_{\ell q}]_{ee33} + [c^{(1)}_{\ell q}]_{ee33}\,, \\
[\hat{c}_{eq}]_{\mu\mu 11} &= [c_{eq}]_{\mu\mu 11} + [c_{ed}]_{\mu\mu 11} - 2[c_{eu}]_{\mu\mu 11}\,, \\
\epsilon_P^{d\mu}(2\ \mathrm{GeV}) &= 0.86[c_{\ell edq}]_{\mu\mu 11} - 0.86[c_{\ell equ}]_{\mu\mu 11} + 0.012[c^{(3)}_{\ell equ}]_{\mu\mu 11}\,, \\
\epsilon_P^{d\tau}(2\ \mathrm{GeV}) &= 0.86[c_{\ell edq}]_{\tau\tau 11} - 0.86[c_{\ell equ}]_{\tau\tau 11} + 0.012[c^{(3)}_{\ell equ}]_{\tau\tau 11}\,, \\
[\hat{c}_{\ell\ell}]_{\mu\mu\mu\mu} &= [c_{\ell\ell}]_{\mu\mu\mu\mu} + 2s^2_{\mathrm{w}}[c_{\ell e}]_{\mu\mu\mu\mu}\,.
\end{aligned}
$$

w/ SM —

or WCs —

GLOBAL ANALYSES TO PRECISION DATA

$$\begin{pmatrix} [\delta g_L^{Wl}]_{ee} \\ [\delta g_L^{Wl}]_{\mu\mu} \\ [\delta g_L^{Wl}]_{\tau\tau} \\ [\delta g_L^{Ze}]_{ee} \\ [\delta g_R^{Ze}]_{ee} \\ [\delta g_L^{Ze}]_{\mu\mu} \\ [\delta g_R^{Ze}]_{\mu\mu} \\ [\delta g_L^{Ze}]_{\tau\tau} \\ [\delta g_R^{Ze}]_{\tau\tau} \\ [\delta g_R^{Wq}]_{11} \\ [\delta g_L^{Zu}]_{11} \\ [\delta g_R^{Zu}]_{11} \\ [\delta g_L^{Zd}]_{11} \\ [\delta g_R^{Zd}]_{11} \\ [\delta g_L^{Zu}]_{22} \\ [\delta g_R^{Zu}]_{22} \\ [\delta g_L^{Zd}]_{22} \\ [\delta g_R^{Zd}]_{22} \\ [\delta g_L^{Zd}]_{33} \\ [\delta g_R^{Zd}]_{33} \end{pmatrix} = \begin{pmatrix} -1.8(2.6) \\ -0.6(2.2) \\ 0.2(3.5) \\ -0.21(28) \\ -0.42(27) \\ 0.2(1.2) \\ 0.0(1.4) \\ -0.09(59) \\ 0.61(62) \\ -3.8(8.1) \\ -7(22) \\ 4(29) \\ -13(35) \\ 10(120) \\ -1.5(3.6) \\ -3.3(5.3) \\ 14(27) \\ 34(46) \\ 3.2(1.7) \\ 22(8.8) \end{pmatrix} \times 10^{-3}, \quad \begin{pmatrix} [c_{ll}]_{eeee} \\ [c_{le}]_{eeee} \\ [c_{ee}]_{eeee} \\ [c_{ll}]_{e\mu\mu e} \\ [c_{ll}]_{ee\mu\mu} \\ [c_{le}]_{e\mu\mu e} \\ [c_{le}]_{ee\mu\mu} \\ [c_{le}]_{\mu\mu ee} \\ [c_{ee}]_{ee\mu\mu} \\ [c_{ll}]_{e\tau\tau e} \\ [c_{ll}]_{ee\tau\tau} \\ [c_{le}]_{ee\tau\tau} \\ [c_{le}]_{\tau\tau ee} \\ [c_{ee}]_{ee\tau\tau} \\ [\hat{c}_{ll}]_{\mu\mu\mu\mu} \\ [c_{ll}]_{\mu\tau\tau\mu} \\ [c_{le}]_{\mu\tau\tau\mu} \end{pmatrix} = \begin{pmatrix} 1.03(38) \\ -0.22(22) \\ 0.19(38) \\ -0.56(80) \\ 0.1(2.0) \\ 11.4(6.8) \\ 0.3(2.2) \\ -0.2(2.1) \\ 0.2(2.3) \\ -0.60(68) \\ 2(11) \\ -2.3(7.2) \\ 1.7(7.2) \\ -1(12) \\ 2(21) \\ 1.5(1.9) \\ 19(15) \end{pmatrix} \times 10^{-2},$$

— *Bresó-Pla, Falkowski, González-Alonso, Monsálvez-Pozo [2301.07036]* —

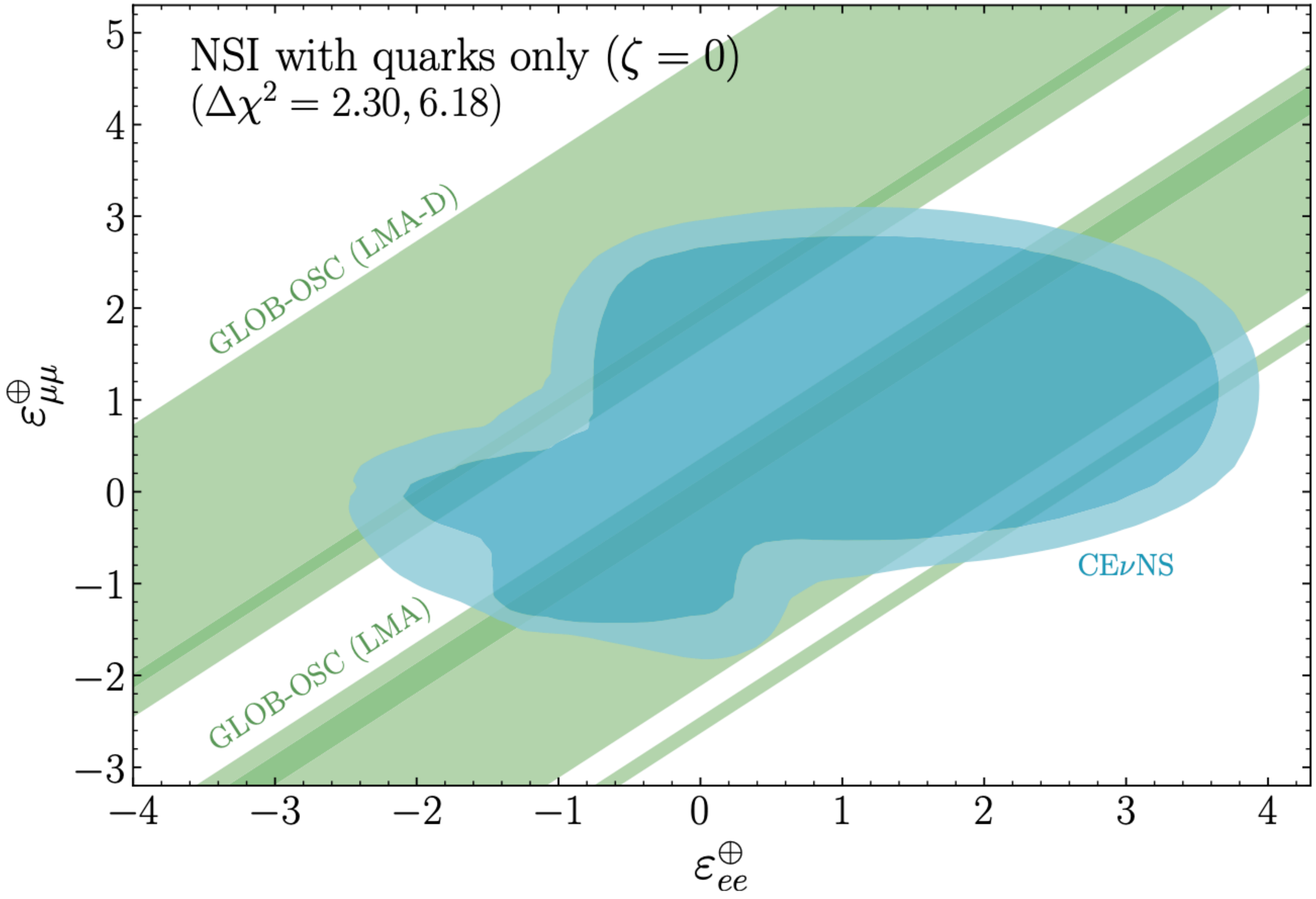
$$\begin{pmatrix} [c_{lq}^{(3)}]_{ee11} \\ [\hat{c}_{eq}]_{ee11} \\ [\hat{c}_{lu}]_{ee11} \\ [\hat{c}_{ld}]_{ee11} \\ [\hat{c}_{eu}]_{ee11} \\ [\hat{c}_{ed}]_{ee11} \\ [c_{lequ}^{(1)}]_{ee11} \\ [c_{ledq}]_{ee11} \\ [c_{lequ}^{(3)}]_{ee11} \\ [\hat{c}_{lq}^{(3)}]_{ee22} \\ [c_{lu}]_{ee22} \\ [\hat{c}_{ld}]_{ee22} \\ [c_{eq}]_{ee22} \\ [c_{eu}]_{ee22} \\ [\hat{c}_{ed}]_{ee22} \\ [\hat{c}_{lq}^{(3)}]_{ee33} \\ [c_{ld}]_{ee33} \\ [c_{eq}]_{ee33} \\ [c_{ed}]_{ee33} \end{pmatrix} = \begin{pmatrix} 0.1(2.8) \\ -4(30) \\ -2.5(8.7) \\ -2(18) \\ -3.1(9.4) \\ -2(17) \\ -0.017(60) \\ -0.018(57) \\ 0.023(66) \\ -61(32) \\ 2.4(8.0) \\ -300(130) \\ -21(28) \\ -87(46) \\ 250(140) \\ -8.5(8.0) \\ -1(10) \\ -3.1(5.1) \\ 18(20) \end{pmatrix} \times 10^{-2}, \quad \begin{pmatrix} [c_{lq}^{(3)}]_{\mu\mu 11} \\ [c_{lq}^{(1)}]_{\mu\mu 11} \\ [c_{lu}]_{\mu\mu 11} \\ [c_{ld}]_{\mu\mu 11} \\ [\hat{c}_{eq}]_{\mu\mu 11} \\ \epsilon_P^{d\mu}(2\ \text{GeV}) \\ [c_{lq}^{(3)}]_{\tau\tau 11} \\ [c_{lequ}^{(3)}]_{\tau\tau 11} \\ \epsilon_P^{d\tau}(2\ \text{GeV}) \end{pmatrix} = \begin{pmatrix} 3.0(3.5) \\ -0.2(5.8) \\ 2.5(6.5) \\ 5(24) \\ 3(41) \\ -0.080(95) \\ -0.3(2.8) \\ -0.3(1.2) \\ 0.93(85) \end{pmatrix} \times 10^{-2}$$

* *Normalized to v*

NON STANDARD INTERACTIONS

Coloma et al JHEP 08 (2023) 032

- *Global Analysis to NC-NSI in oscillation + CEvNS*



$$\varepsilon^{\oplus}_{\alpha\beta} = \varepsilon^{e,V}_{\alpha\beta} + (2 + Y^{\oplus}_n)\varepsilon^{u,V}_{\alpha\beta} + (1 + 2Y^{\oplus}_n)\varepsilon^{d,V}_{\alpha\beta}$$

NON STANDARD INTERACTIONS

Coloma et al JHEP 08 (2023) 032

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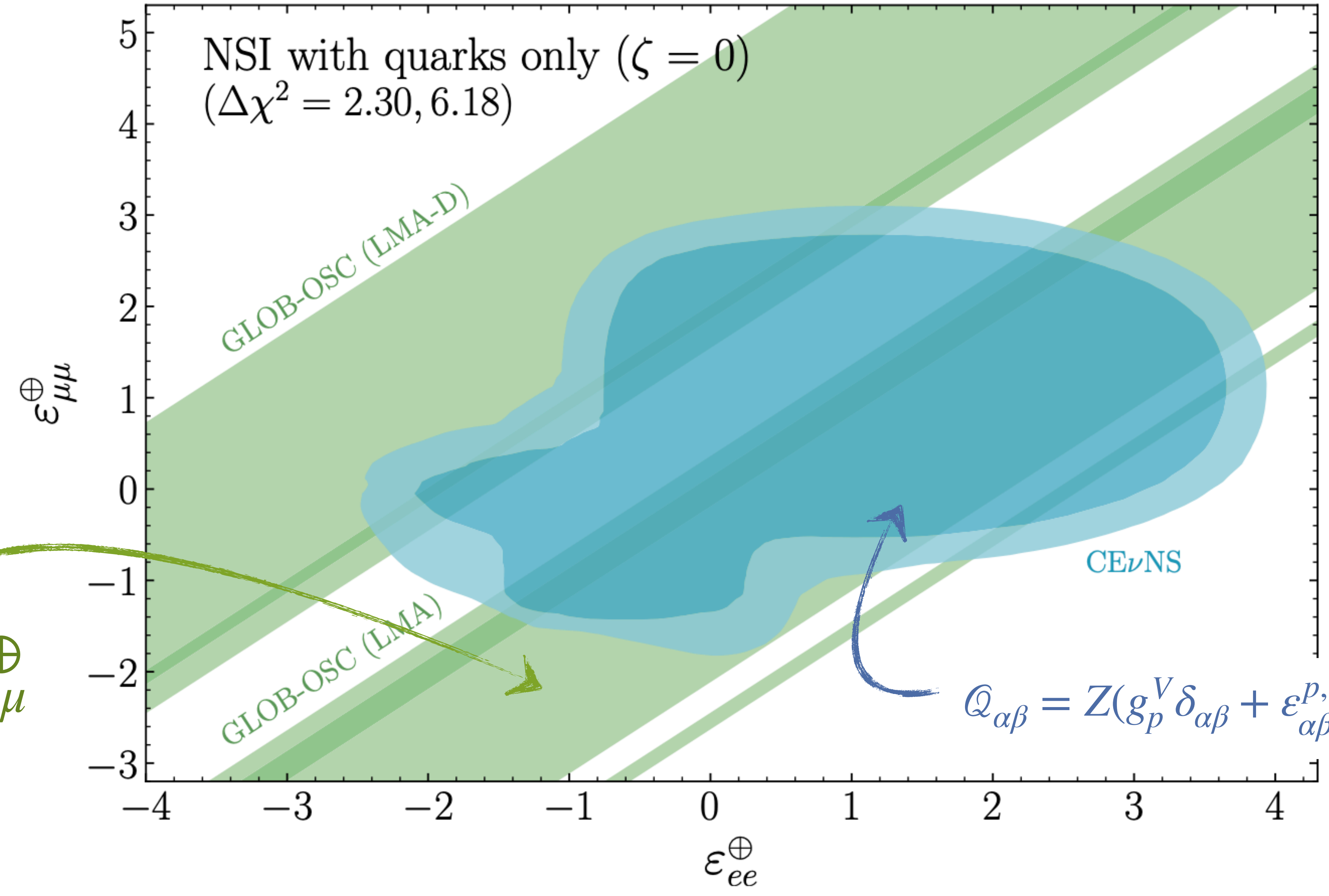

$\varepsilon^{\oplus}_{ee} - \varepsilon^{\oplus}_{\mu\mu}$

$\mathcal{Q}_{\alpha\beta} = Z(g_p^V \delta_{\alpha\beta} + \varepsilon^{p,V}_{\alpha\beta}) + N(g_n^V \delta_{\alpha\beta} + \varepsilon^{n,V}_{\alpha\beta})$

$$\varepsilon^{\oplus}_{\alpha\beta} = \varepsilon^{e,V}_{\alpha\beta} + (2 + Y_n^{\oplus})\varepsilon^{u,V}_{\alpha\beta} + (1 + 2Y_n^{\oplus})\varepsilon^{d,V}_{\alpha\beta}$$

NON STANDARD INTERACTIONS

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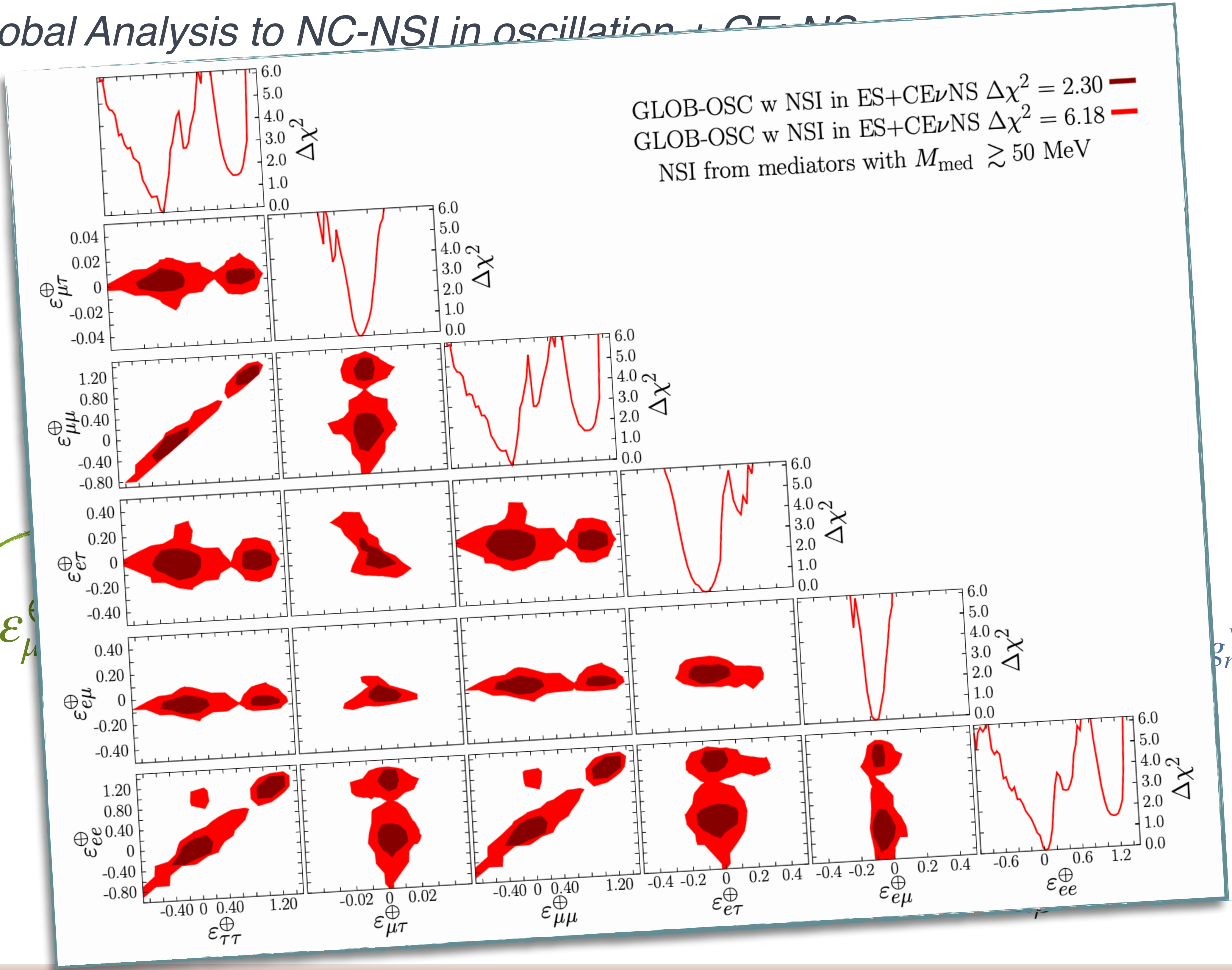
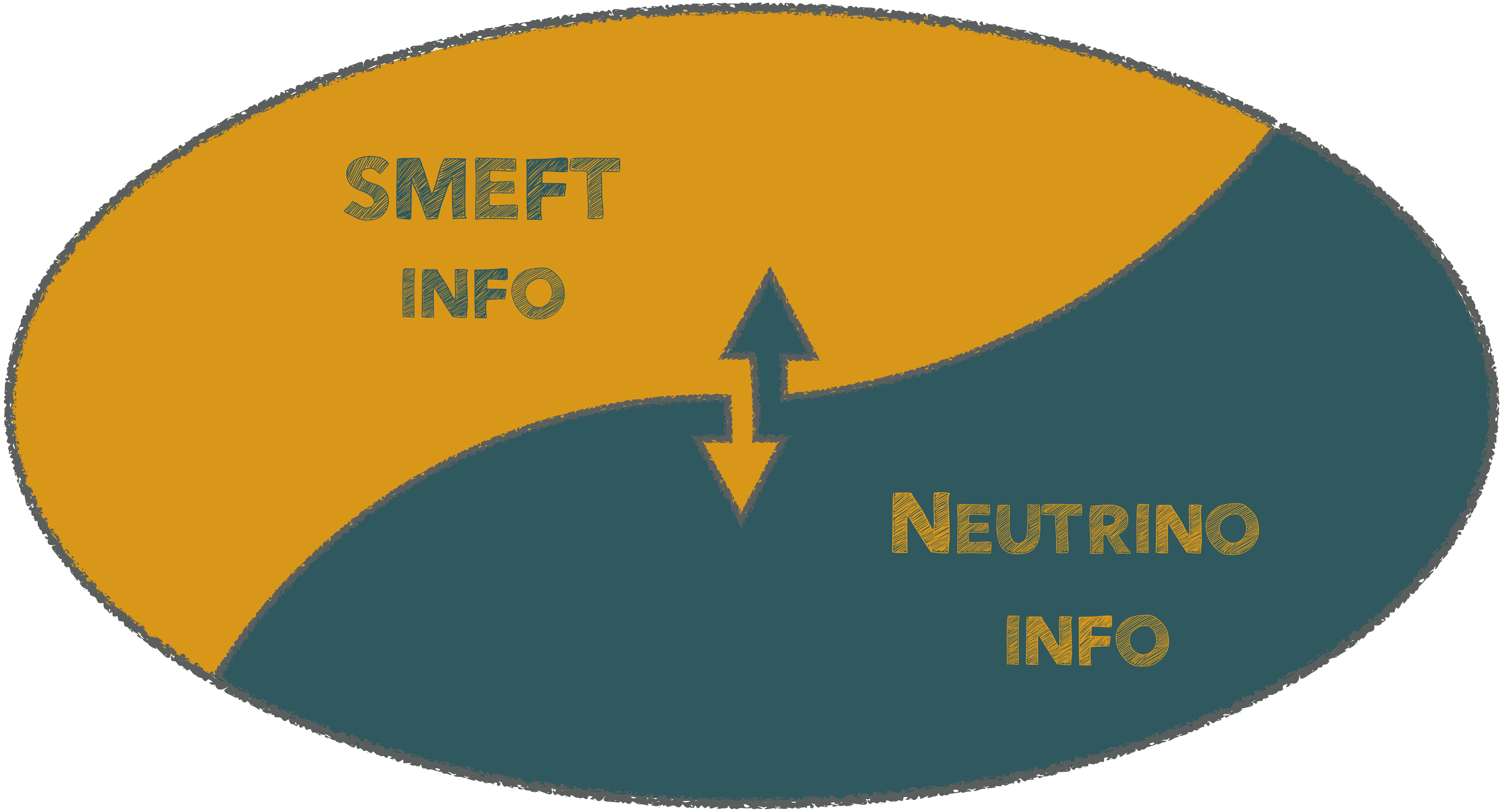


$\varepsilon_{ee}^{\oplus} - \varepsilon_{\mu}$

$n^V \delta_{\alpha\beta} + \varepsilon_{\alpha\beta}^{n,V})$

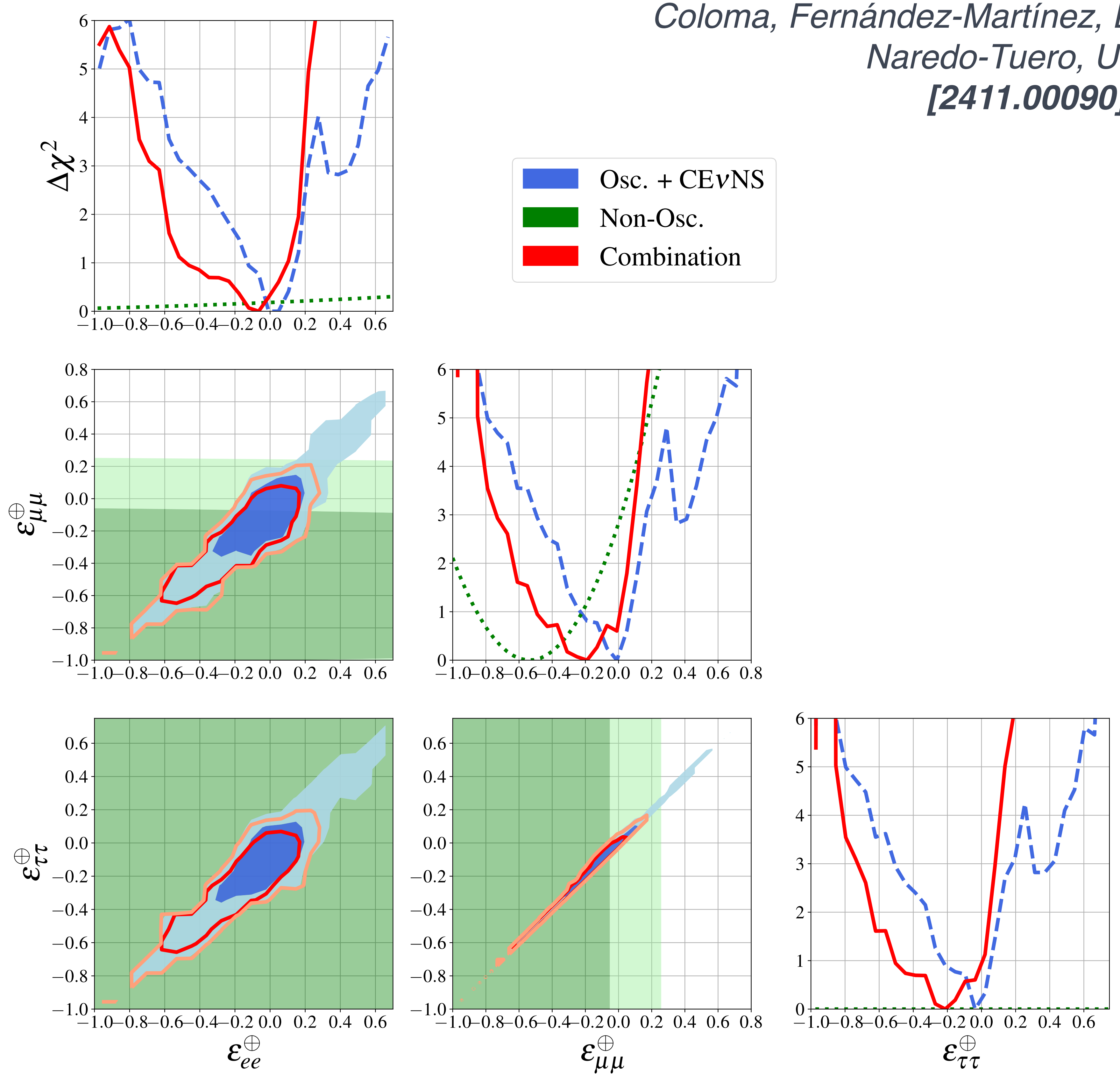
Let's combine both analyses


SMEFT INFO

Neutrino INFO

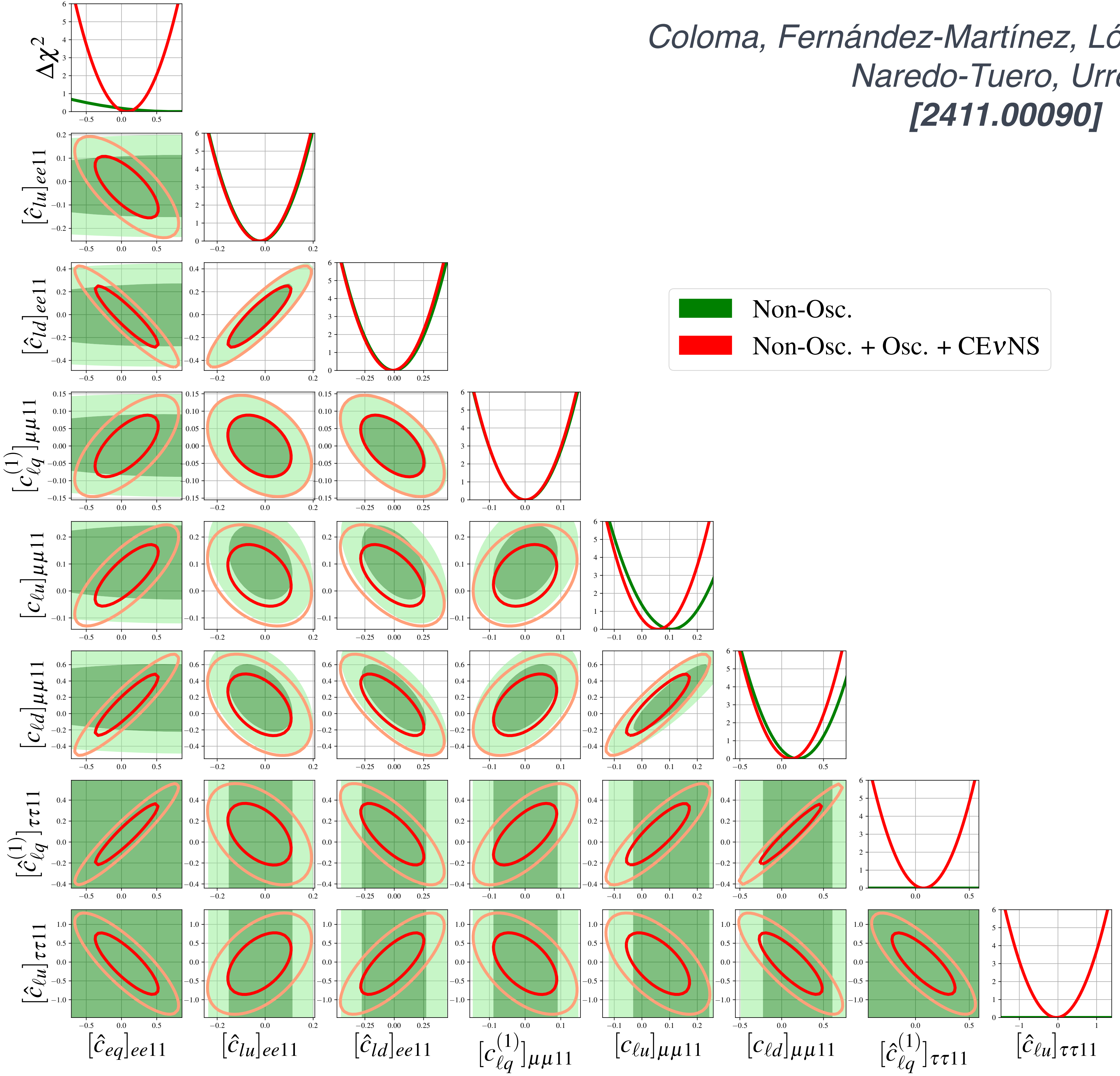
SMEFT INPUT FOR NSI

Coloma, Fernández-Martínez, López-Pavón, XM,
Naredo-Tuero, Urrea
[2411.00090]



NSI INPUT FOR SMEFT

Coloma, Fernández-Martínez, López-Pavón, XM, Naredo-Tuero, Urrea
[2411.00090]



NSI INPUT FOR SMEFT

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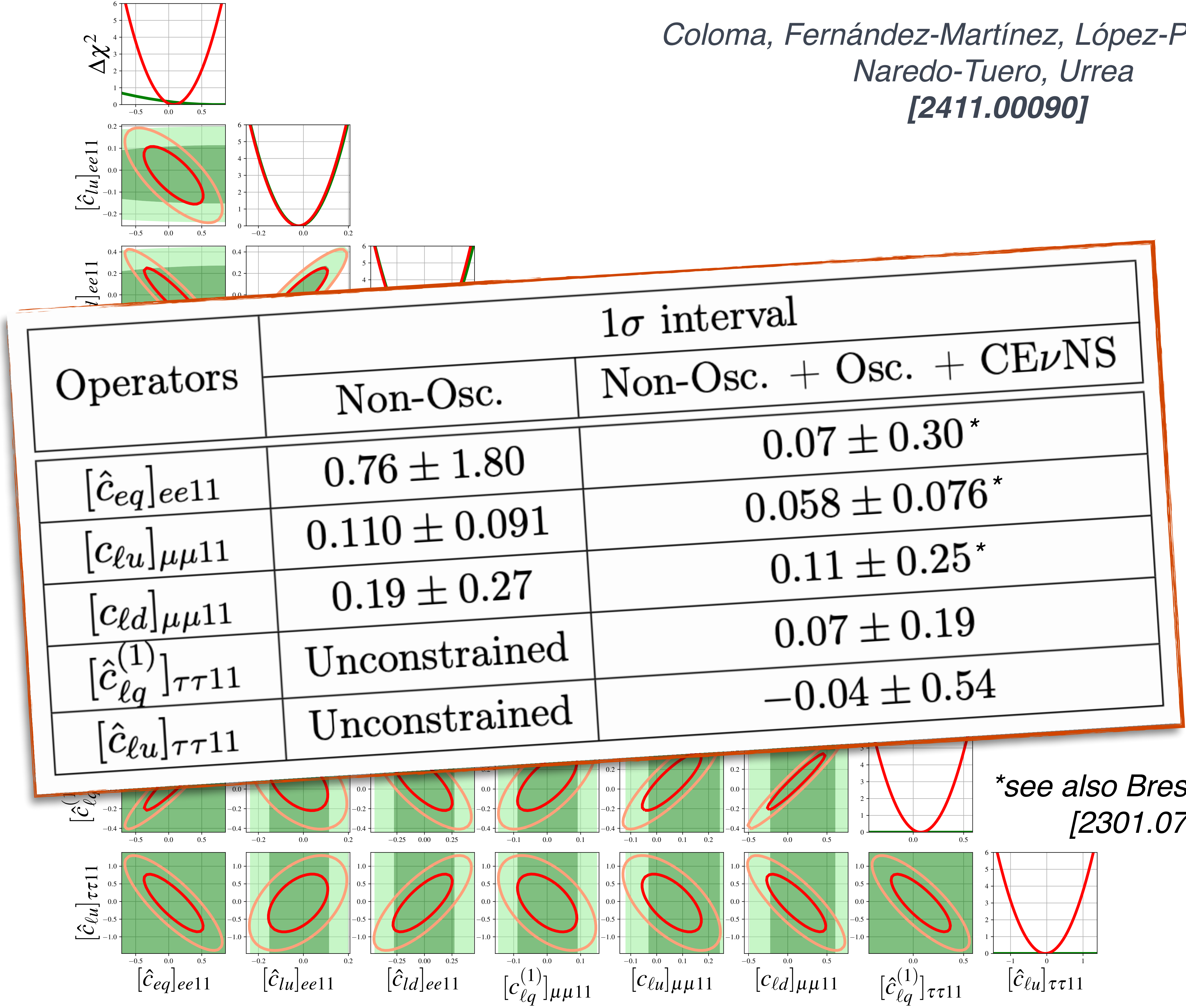


Operators	1σ interval	
	Non-Osc.	Non-Osc. + Osc. + CEνNS
$[\hat{c}_{eq}]ee11$	0.76 ± 1.80	$0.07 \pm 0.30^*$
$[c_{\ell u}]\mu\mu11$	0.110 ± 0.091	$0.058 \pm 0.076^*$
$[c_{\ell d}]\mu\mu11$	0.19 ± 0.27	$0.11 \pm 0.25^*$
$[\hat{c}^{(1)}_{\ell q}]\tau\tau11$	Unconstrained	0.07 ± 0.19
$[\hat{c}_{\ell u}]\tau\tau11$	Unconstrained	-0.04 ± 0.54

**see also Bresó-Pla et al*
[2301.07036]

SUMMARY — PART III

☑ *Previous SMEFT bounds help* ***constraining NSI***

  - *Mainly from $\varepsilon_{\mu\mu}$ + strong correlations*

☑ *Neutrino oscillations + CEvNS* ***improve SMEFT global picture***

  - *Doesn't close flat directions, but improve some bounds*
  - *New bounds in the $\tau\ell$ sector*
  - *Induce strong(er) correlations*

— PART IV —

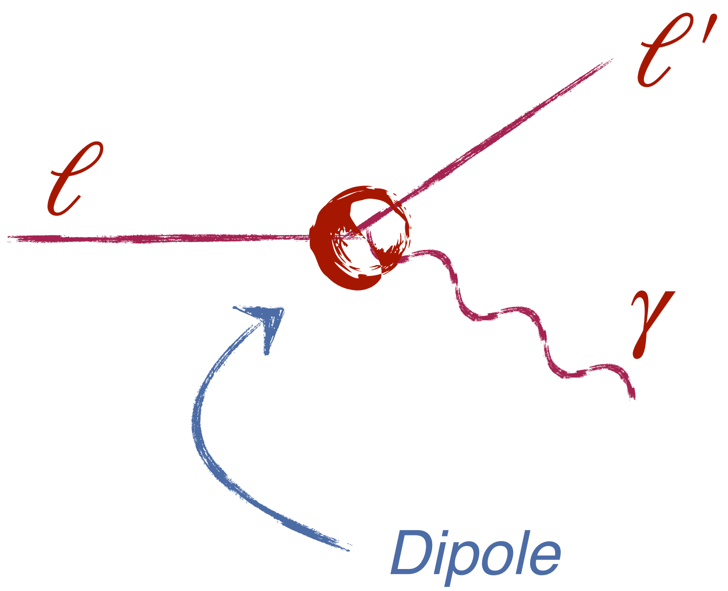
GLOBAL ANALYSIS OF LFV OPERATORS

arXiv: 2403.09772

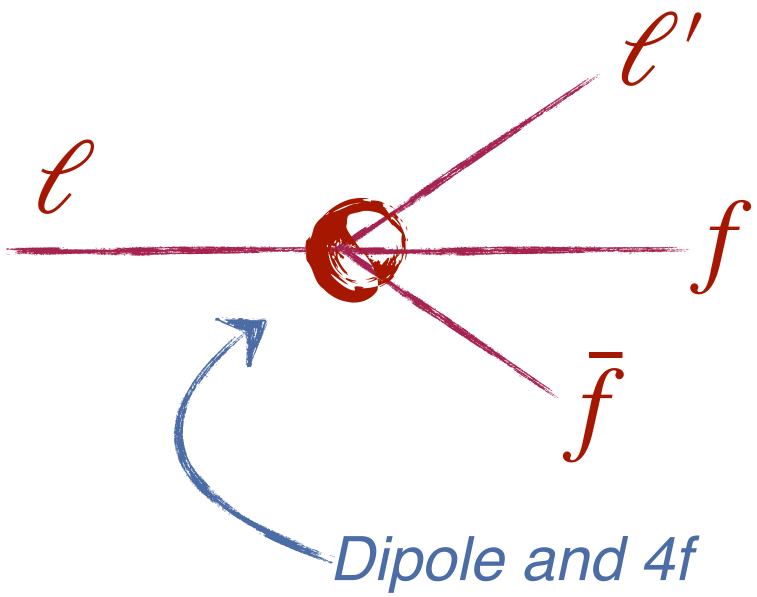
Global Lepton Flavour Violating Constraints on New Physics

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

CLFV IN SMEFT (DIM 6)



Dipole



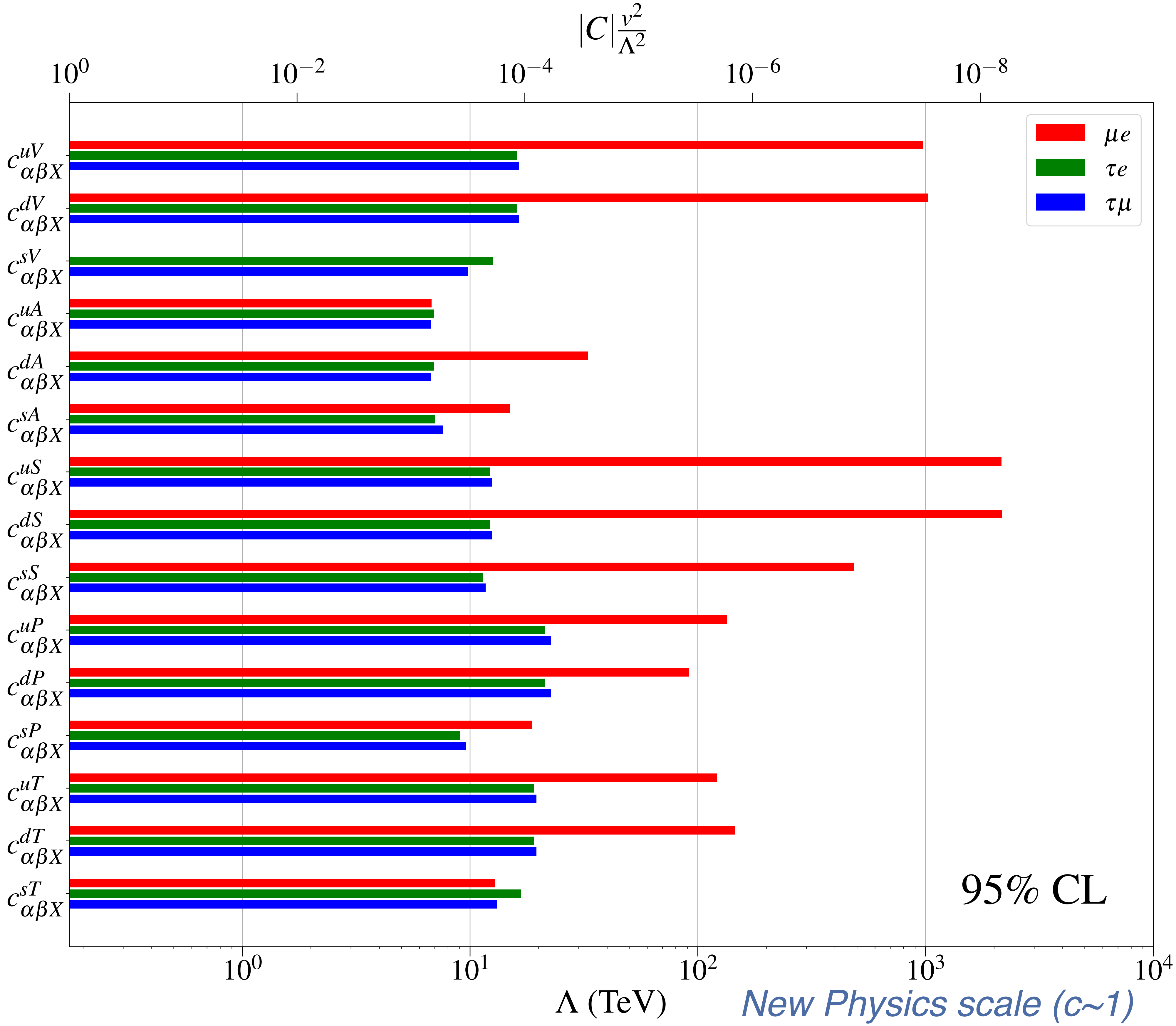
Dipole and 4f

- ***Plenty of work in this direction***

  Raidal&Santamaria(96), Kuno&Okada(99), Brignole&Rossi(04), Ibarra et al (04), Carpentier&Davidson(10), Crivellin et al(13), Celis et al(14), Pruna&Signer(14), Efrati et al(15), Feruglio et al(15), Davidson(16), Crivellin et al(17), Aebischer et al(18), González et al(21), Ardu&Davidson(21), Calibbi et al (21), Calibbi et al (22), and many others

FIRST LOOK AT THE EFT STATUS

some WC (see later)



New Physics scale (c~1)

LOOKING FOR A GLOBAL PICTURE

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

— CHALLENGING GOAL —

- *Many operators and observables*
- *We cannot linearize the EFT dependence*

— No interference with SM —

LOOKING FOR A GLOBAL PICTURE

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

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Everything is possible
when you have the proper tools

LOOKING FOR A GLOBAL PICTURE

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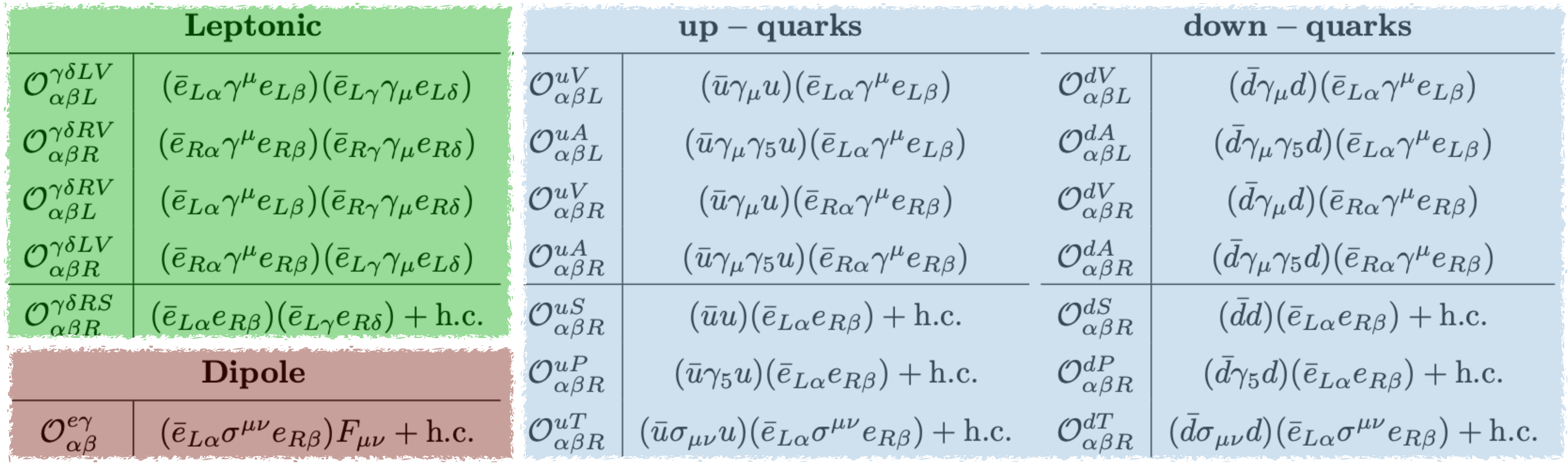
— No interference with SM —

Everything is possible
when you have the proper tools

Daniel Naredo

SCENARIOS/FRAMEWORKS

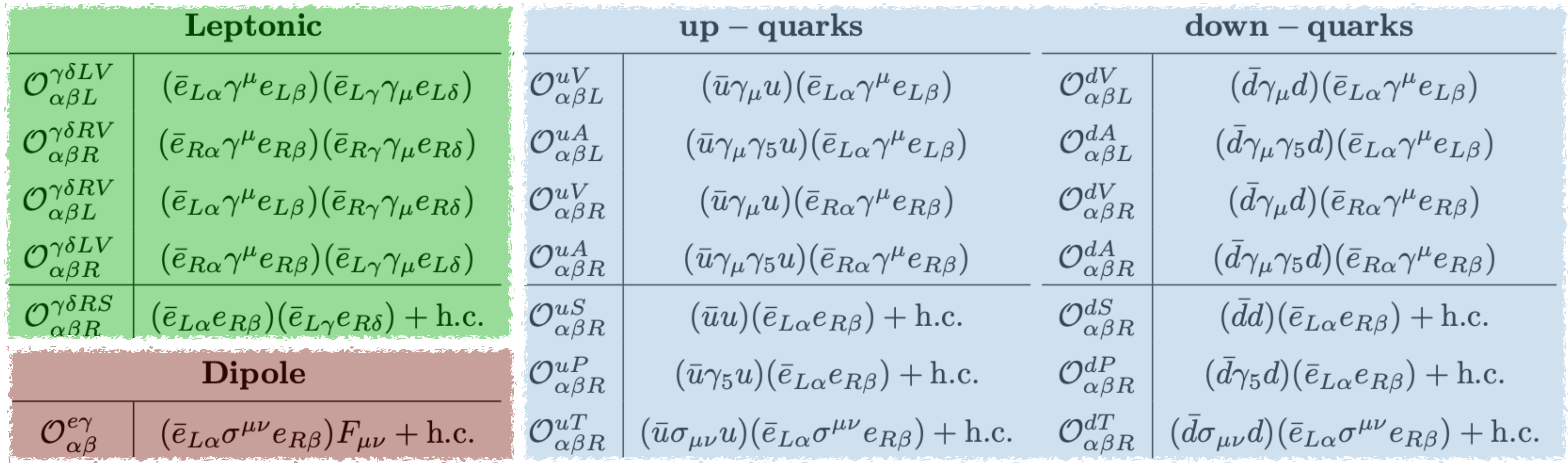


Leptonic		**up − quarks**		**down − quarks**	
$\mathcal{O}^{\gamma\delta LV}_{\alpha\beta L}$	$(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})(\bar{e}_{L\gamma}\gamma_{\mu}e_{L\delta})$	$\mathcal{O}^{uV}_{\alpha\beta L}$	$(\bar{u}\gamma_{\mu}u)(\bar{e}_{L\alpha}\gamma^{\mu}e_{L\beta})$	$\mathcal{O}^{dV}_{\alpha\beta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

— LEFT —

All operators are independent

SCENARIOS/FRAMEWORKS



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

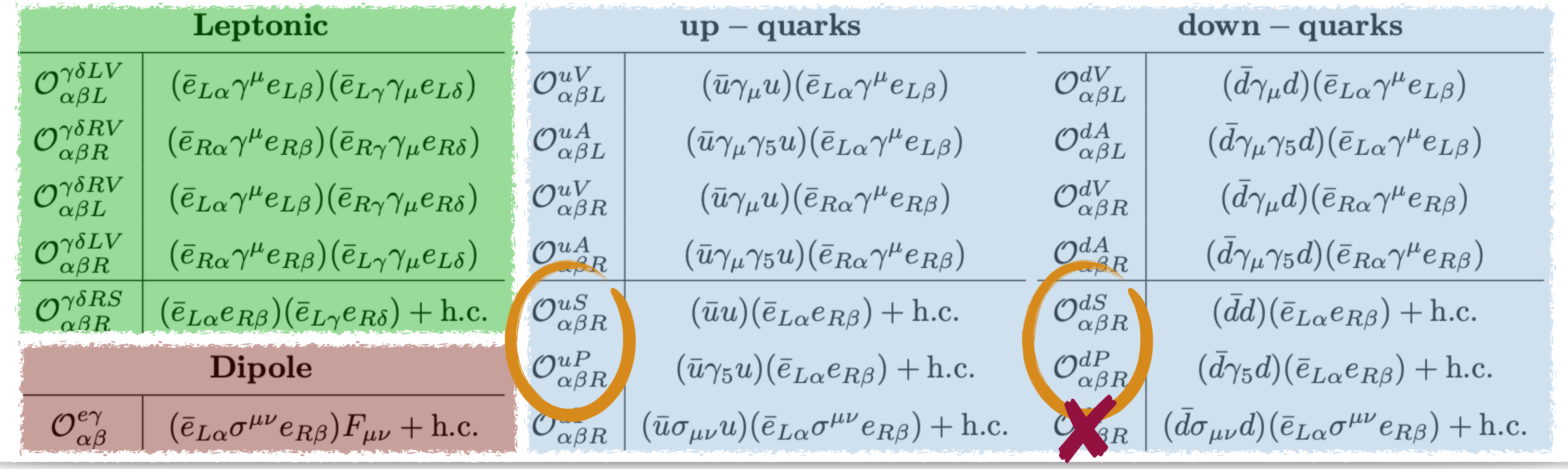
up – quarks		down – quarks	
$\mathcal{O}^{uV}_{\alpha\beta L}$	$(\bar{u}\gamma_\mu u)(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})$	$\mathcal{O}^{dV}_{\alpha\beta L}$	$(\bar{d}\gamma_\mu d)(\bar{e}_{L\alpha}\gamma^\mu e_{L\beta})$
$\mathcal{O}^{uA}_{\alpha\beta L}$	$(\bar{u}\gamma_\mu\gamma_5 u)(\bar{e}_{L\alpha}\gamma^\mu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

— LEFT —

Back Up

All operators are independent

SCENARIOS/FRAMEWORKS



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

less freedom

— LEFT —

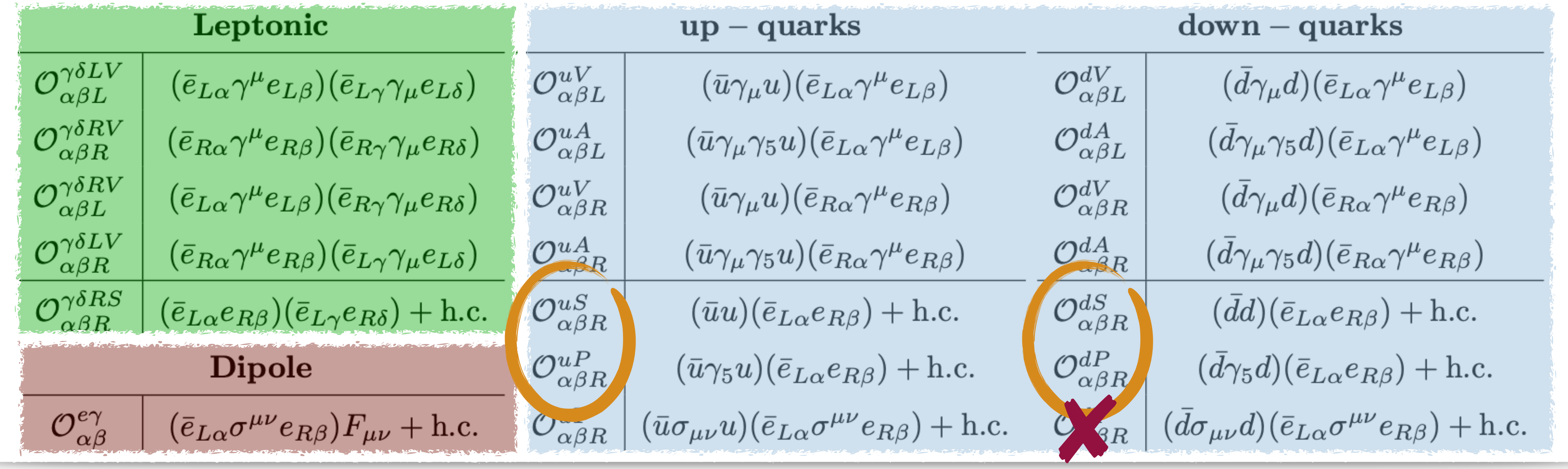
Back Up

All operators are independent

— SMEFT (3flavor) —

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

SCENARIOS/FRAMEWORKS



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

less freedom

— LEFT —

Back Up

All operators are independent

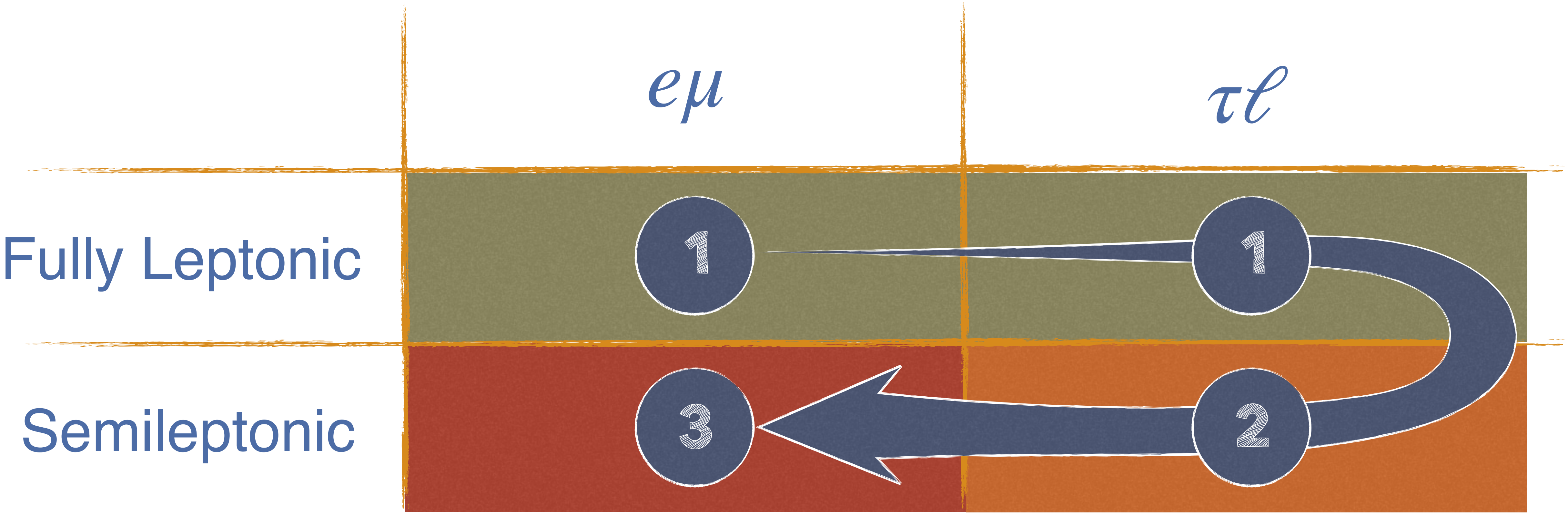
— SMEFT (3flavor) —

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

— SMEFT (2flavor) —

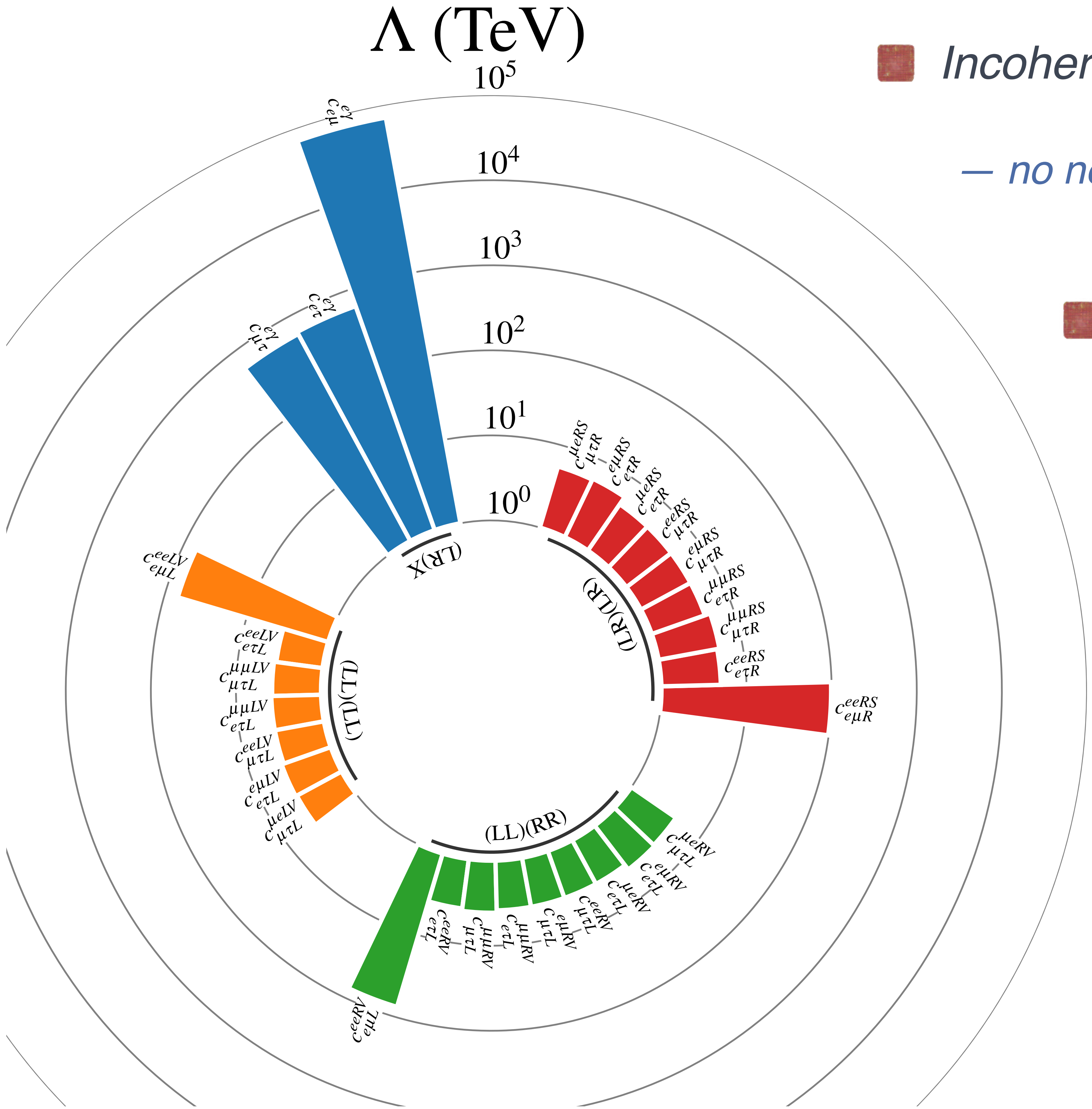
SMEFT induced relations. Only light quarks u,d

— GLOBAL RESULTS —



	$e\mu$	$\tau\ell$
Fully Leptonic	1	1
Semileptonic	3	2

FULLY LEPTONIC OPERATORS



- *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.:*

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

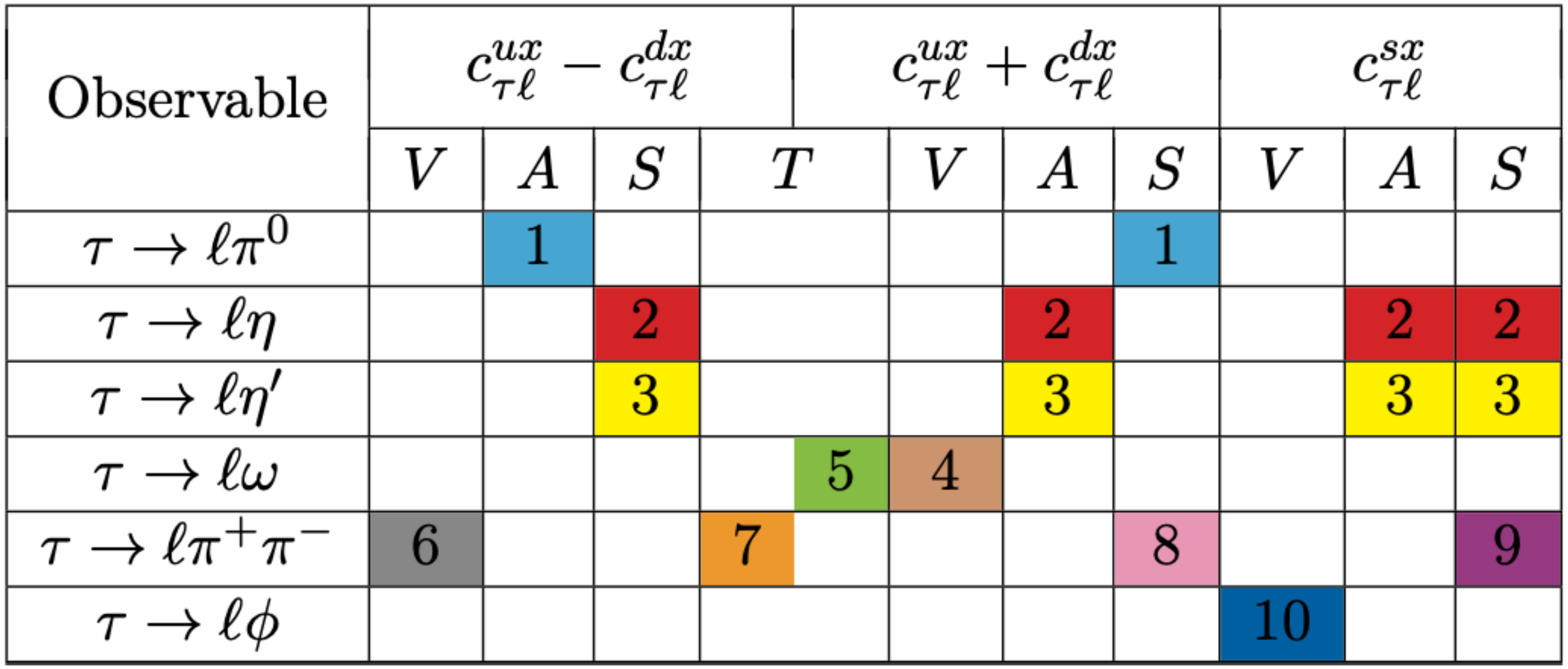
$$BR\left(\tau \to \ell\phi\right) \propto \sum_{X=L,R} \left\{\left(\frac{m_\tau^2}{m_\phi^2} + 1 - 2\frac{m_\phi^2}{m_\tau^2}\right)\left|c^{sV}_{\tau\ell X}\right|^2 + 4\left(\frac{f_{T,\phi}}{f_\phi}\right)^2\left(2\frac{m_\tau^2}{m_\phi^2} - 1 - \frac{m_\phi^2}{m_\tau^2}\right)\left|c^{sT}_{\tau\ell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

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.:*

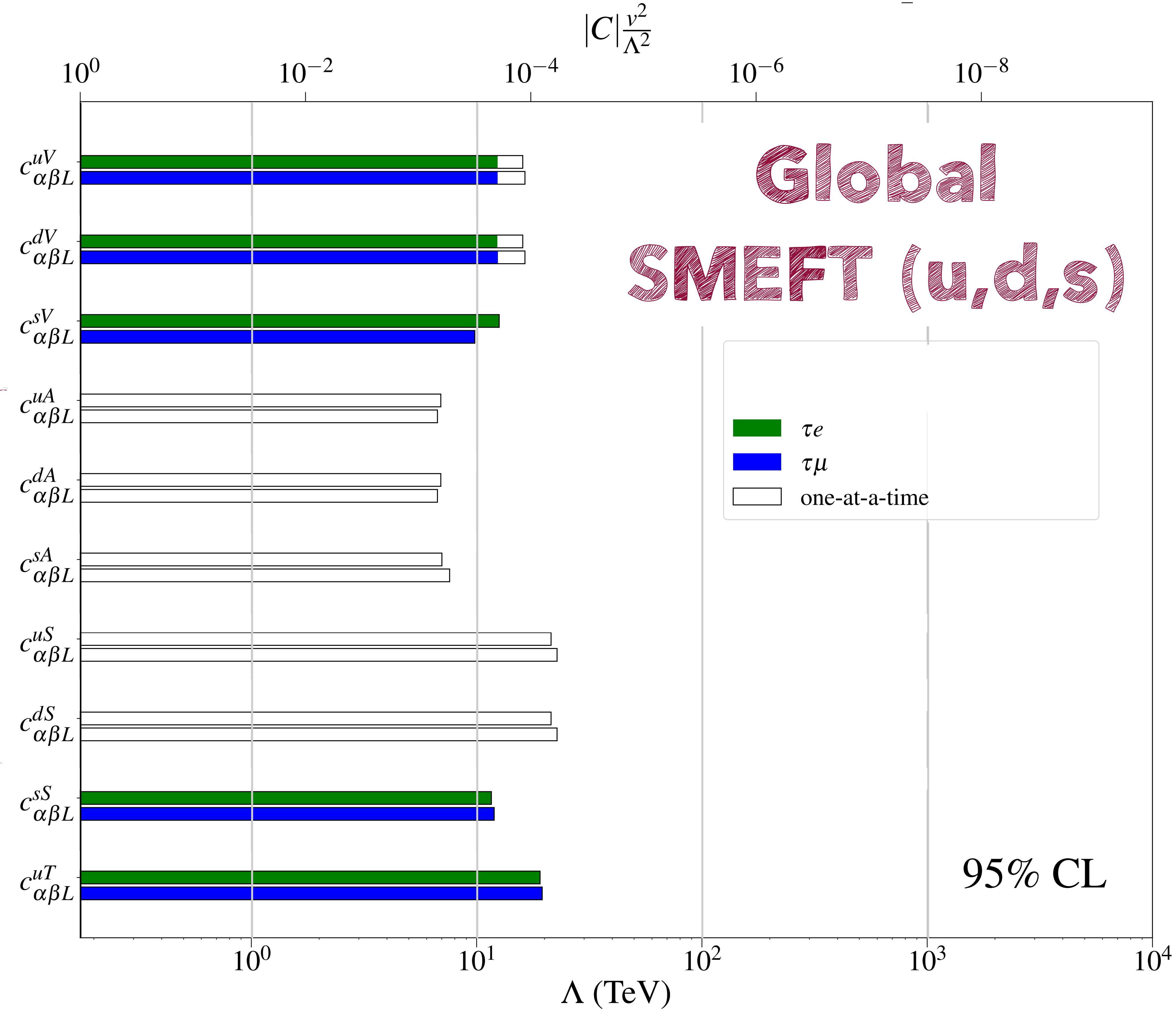


Observable	$c^{ux}_{\tau\ell} - c^{dx}_{\tau\ell}$				$c^{ux}_{\tau\ell} + c^{dx}_{\tau\ell}$				$c^{sx}_{\tau\ell}$		
	V	A	S	T		V	A	S	V	A	S
$\tau \to \ell\pi^0$		1						1			
$\tau \to \ell\eta$			2				2			2	2
$\tau \to \ell\eta'$			3				3			3	3
$\tau \to \ell\omega$					5	4					
$\tau \to \ell\pi^+\pi^-$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

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

— involving A and S WCs —

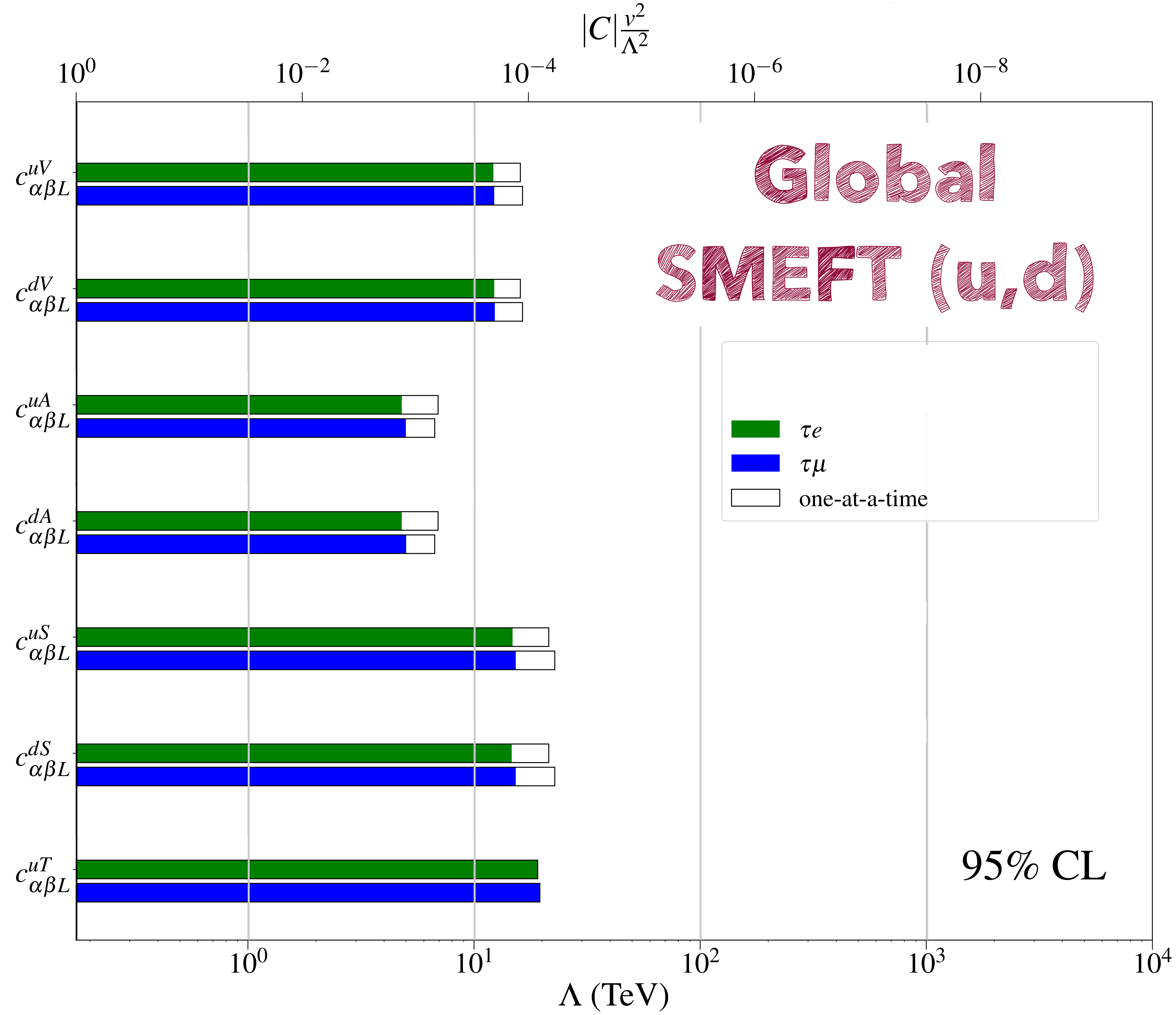
SEMILEPTONIC OPERATORS WITH TAUS



globally unbounded

SEMILEPTONIC OPERATORS WITH TAUS

globally bounded



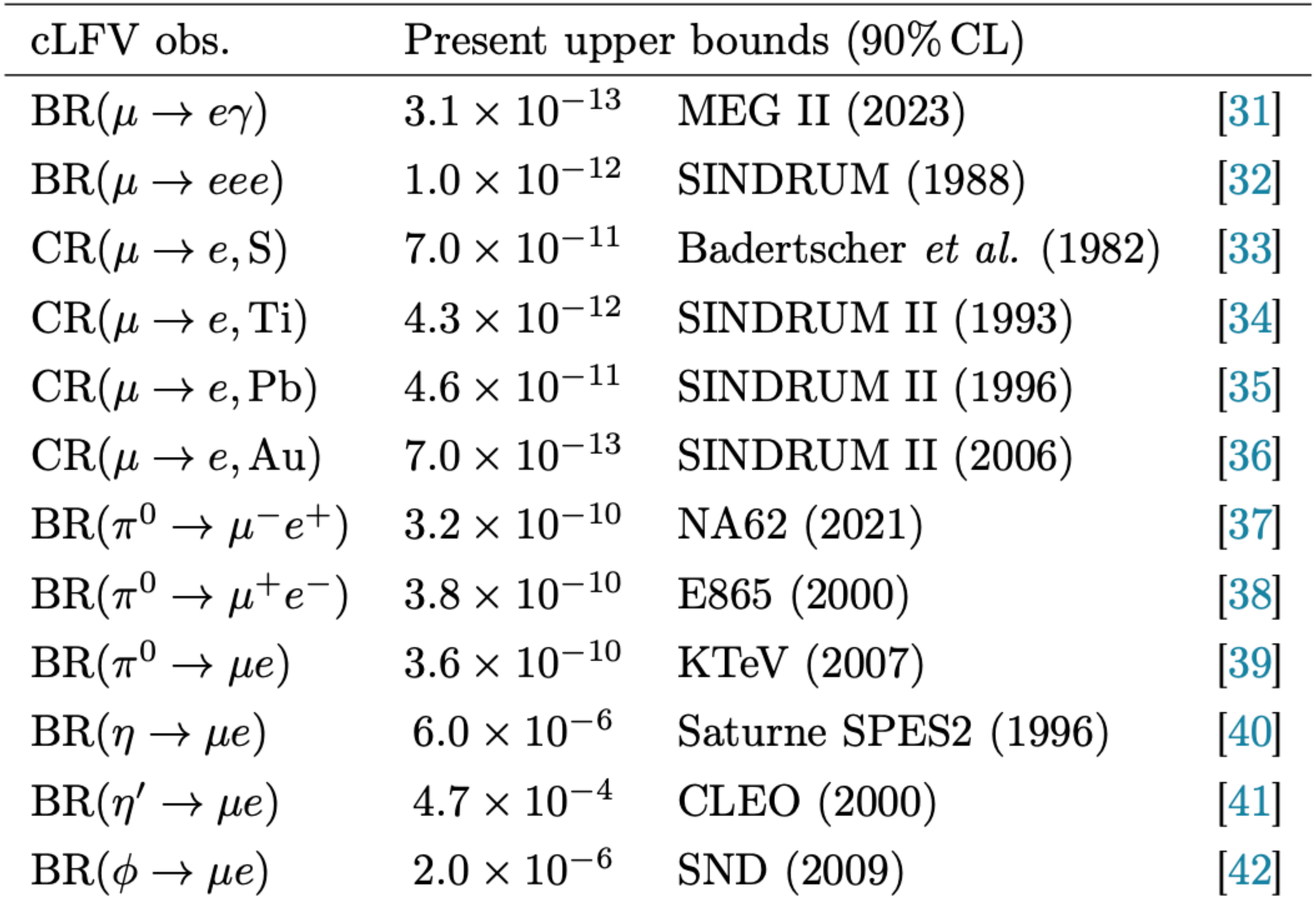
— GLOBAL RESULTS —

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

Strong Correlations!!!

SEMILEPTONIC OPERATORS MU-E

- *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… —

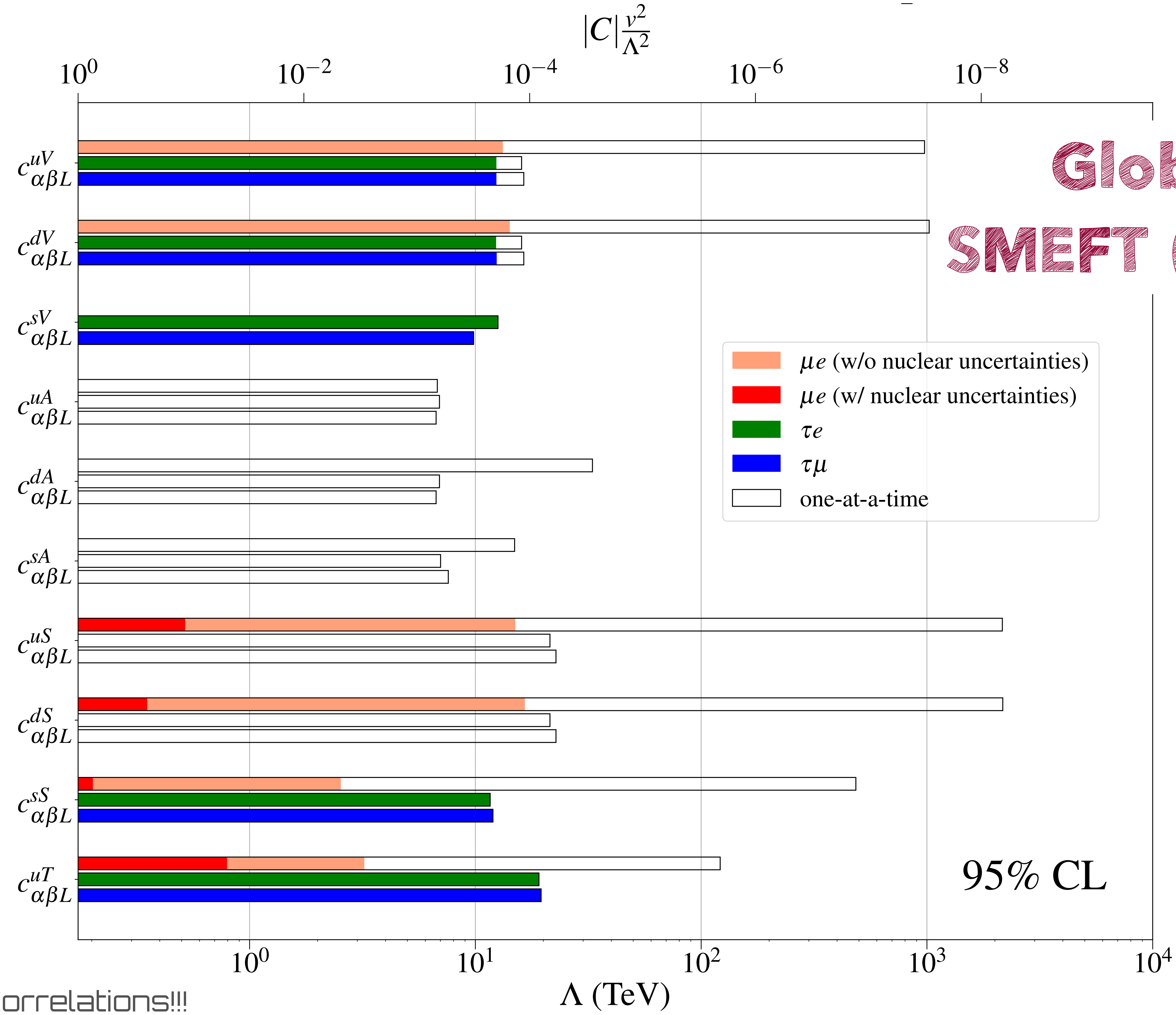
  - *Spin-Dependent for A, P, T operators*

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

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

  — Also needed in a global picture! —

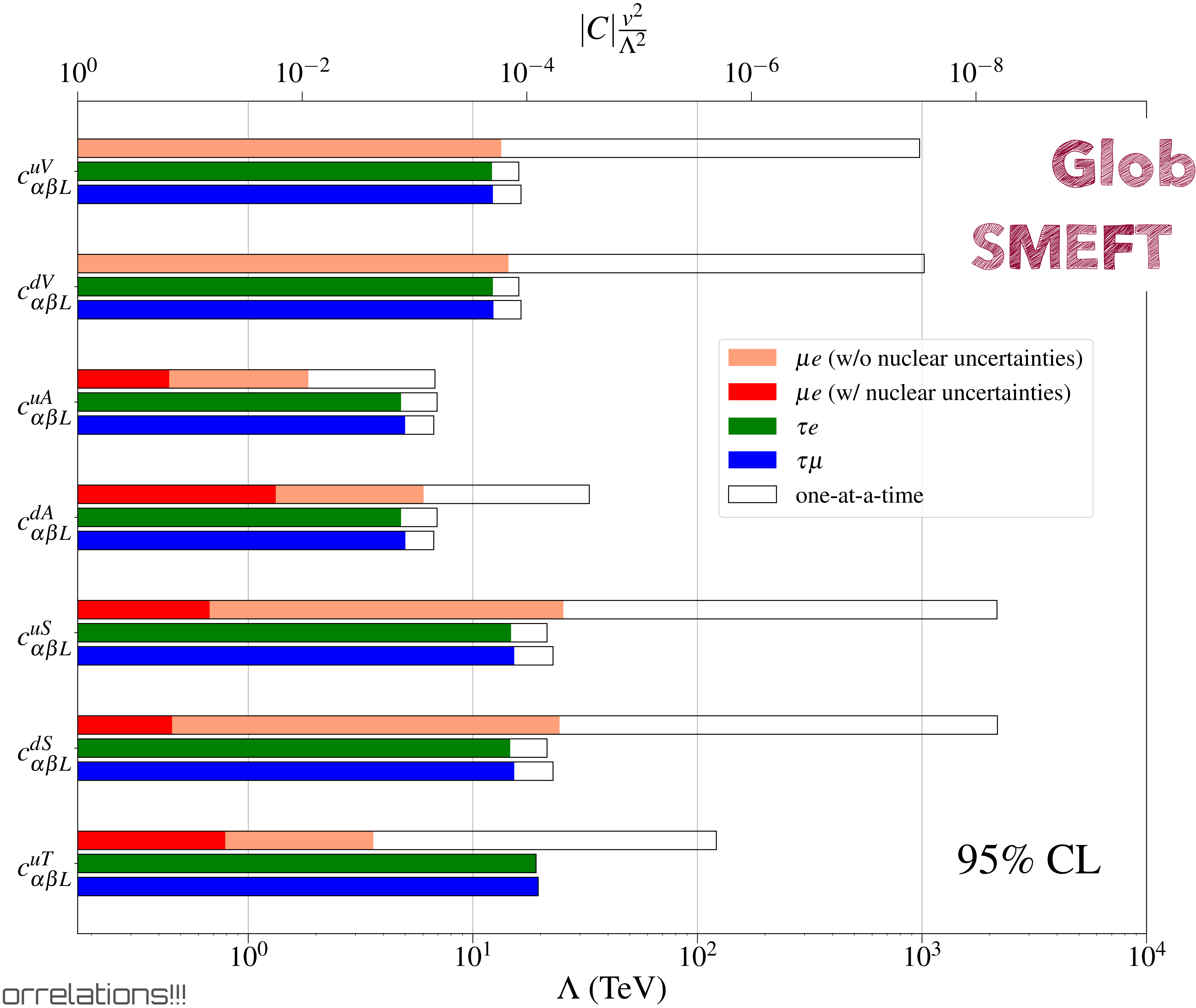
SEMILEPTONIC OPERATORS MU-E



Global SMEFT (u,d,s)

Strong Correlations!!!

SEMILEPTONIC OPERATORS MU-E

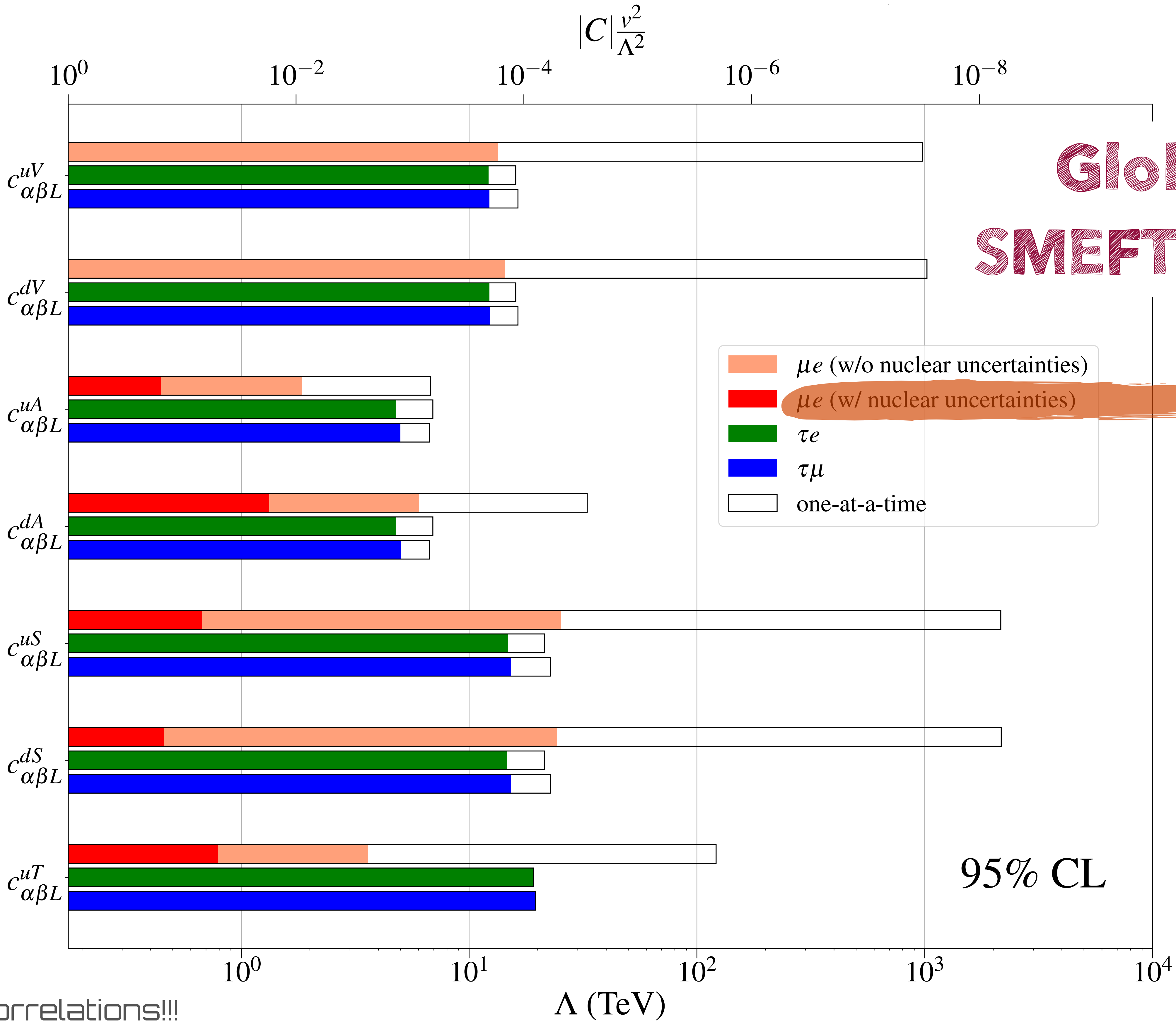


Global

SMEFT (u,d)

Strong Correlations!!!

SEMILEPTONIC OPERATORS MU-E



Global SMEFT (u,d)

Strong Correlations!!!

— CAN WE IMPROVE IT WITH NEUTRINOS? —

Neutrino oscillations — zero distance effects

[Biggio et al'09]

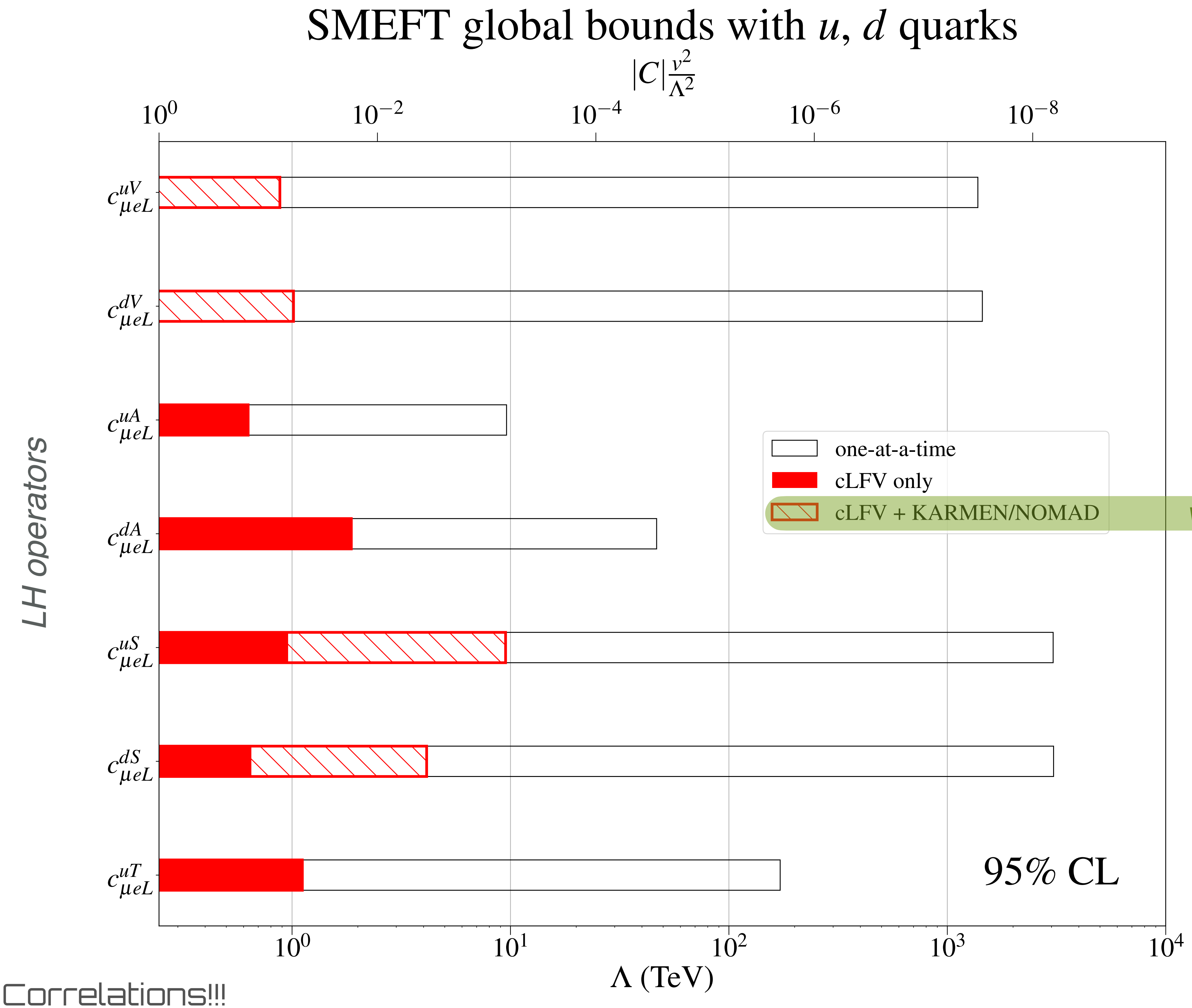
arXiv: 2411.00090

Improving the global SMEFT picture with bounds on neutrino NSI

Pilar Coloma, Enrique Fernández-Martínez, Jacobo López-Pavón, XM,
Daniel Naredo-Tuero *and Salvador Urrea*

NEUTRINO INPUT FOR cLFV

Coloma, Fernández-Martínez, López-Pavón, XM, Naredo-Tuero, Urrea ***[2411.00090]***



ν osc at zero-distance

Strong Correlations!!!

CAN NEUTRINOS HELP PROBING THE SM EFFECTIVE THEORY?

— one-at-a-time —

NEUTRINO DATA IRRELEVANT

— compared to charged leptons —

— Global Picture —

YES!

CONCLUSIONS

- SM EFTs are well motivated and powerful tools for model-independent analyses

  — many new parameters, challenging to constrain them all —

- Potential flat/poorly constrained directions make it harder

  — we need more independent observables—

- NSI formalism provides new data
  - Improves global picture for LFC operators

    — improve bounds, new bounds for τ, stronger correlations —

  - Closed flat directions for LFV operators

    — zero distance effects for μe —

Neutrino oscillations and CEvNS
need to be included in future SMEFT global analyses

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Newtrinos
Effective Portals to New Physics

INFN

Thank you!

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DI RIPRESA E RESILIENZA

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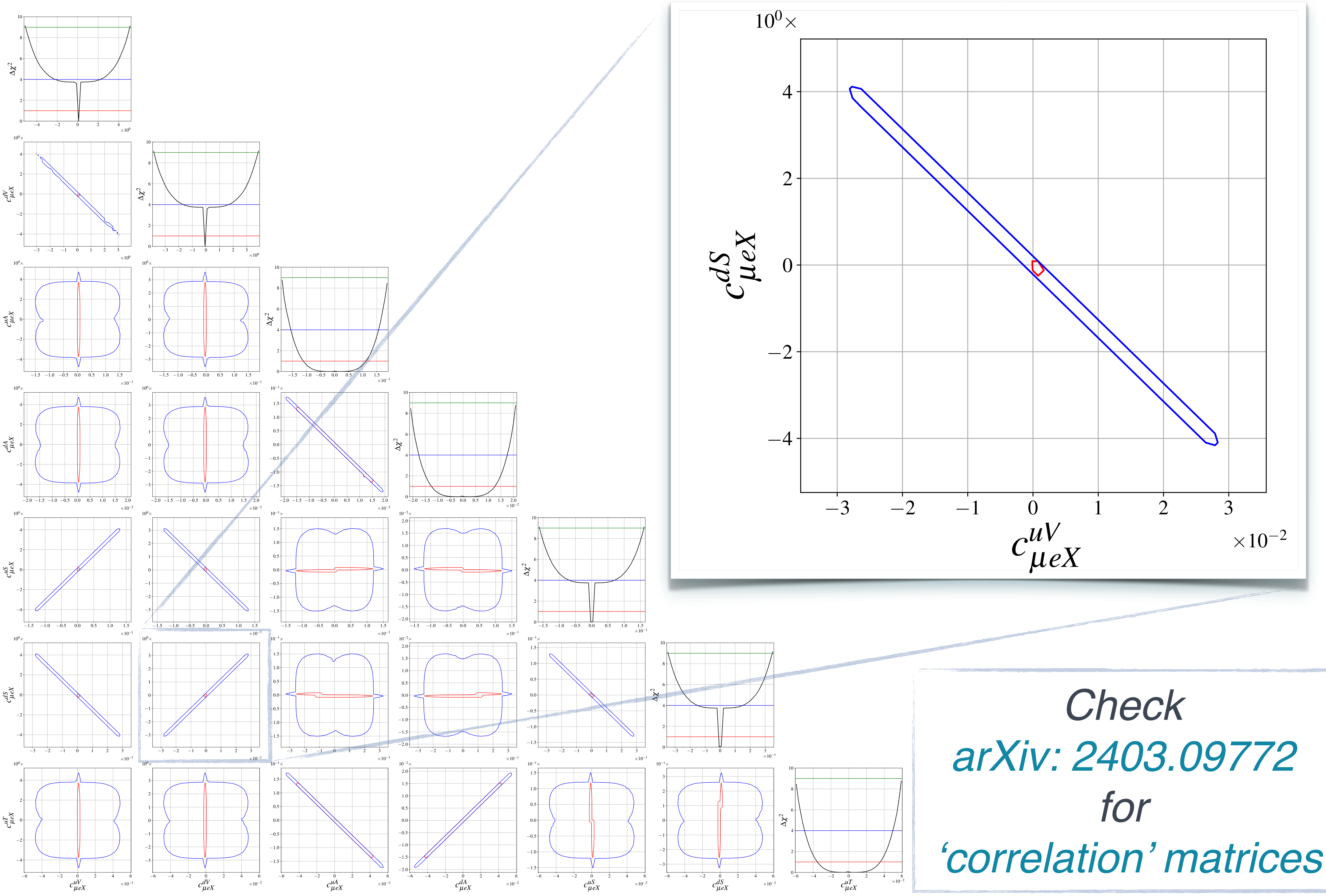
WARNING

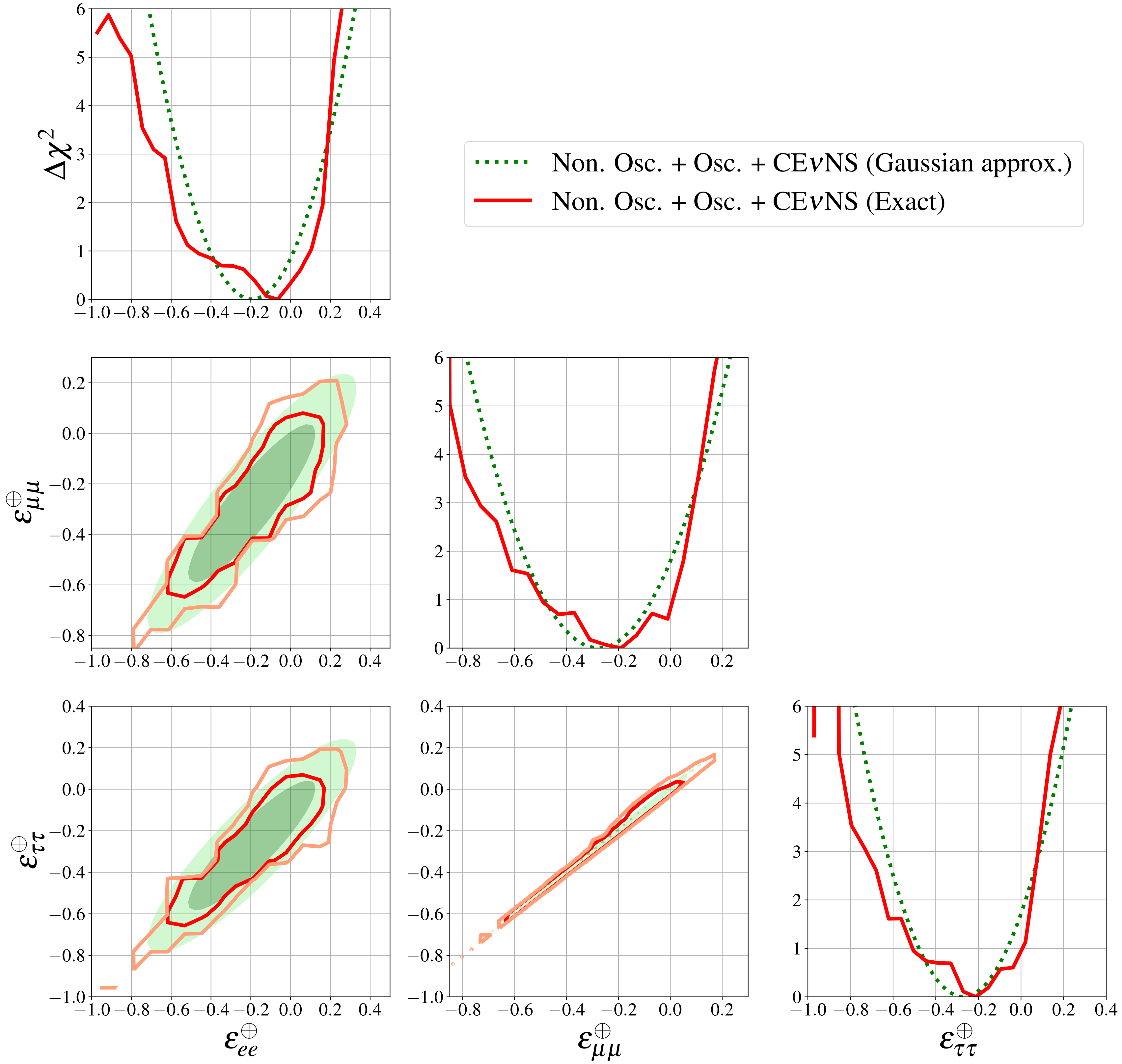
Does a flat direction mean there are unbounded operators?

STRONG CORRELATIONS



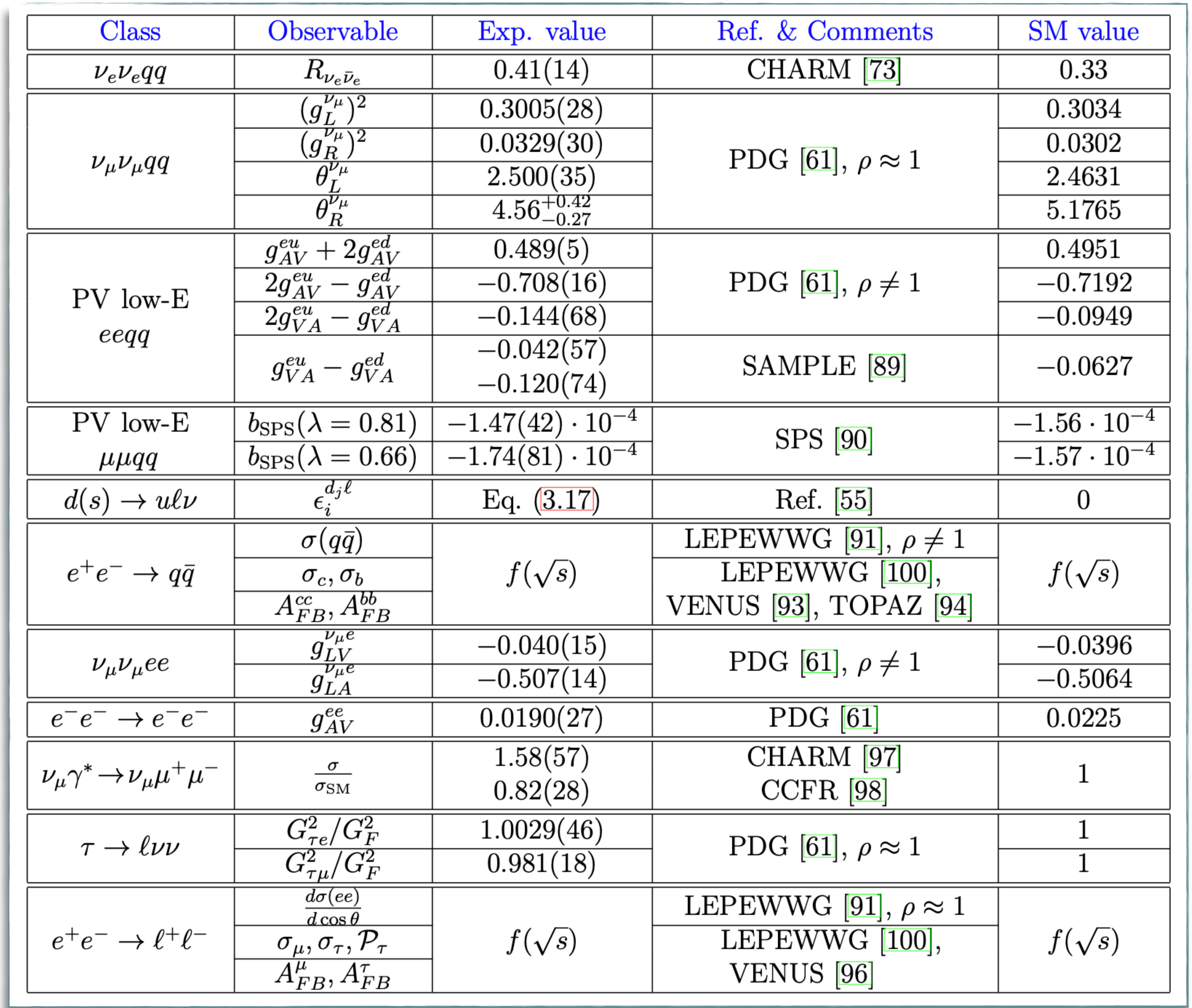
Check
arXiv: 2403.09772
for
'correlation' matrices

GAUSSEAN APPROX



PREVIOUS GLOBAL ANALYSES

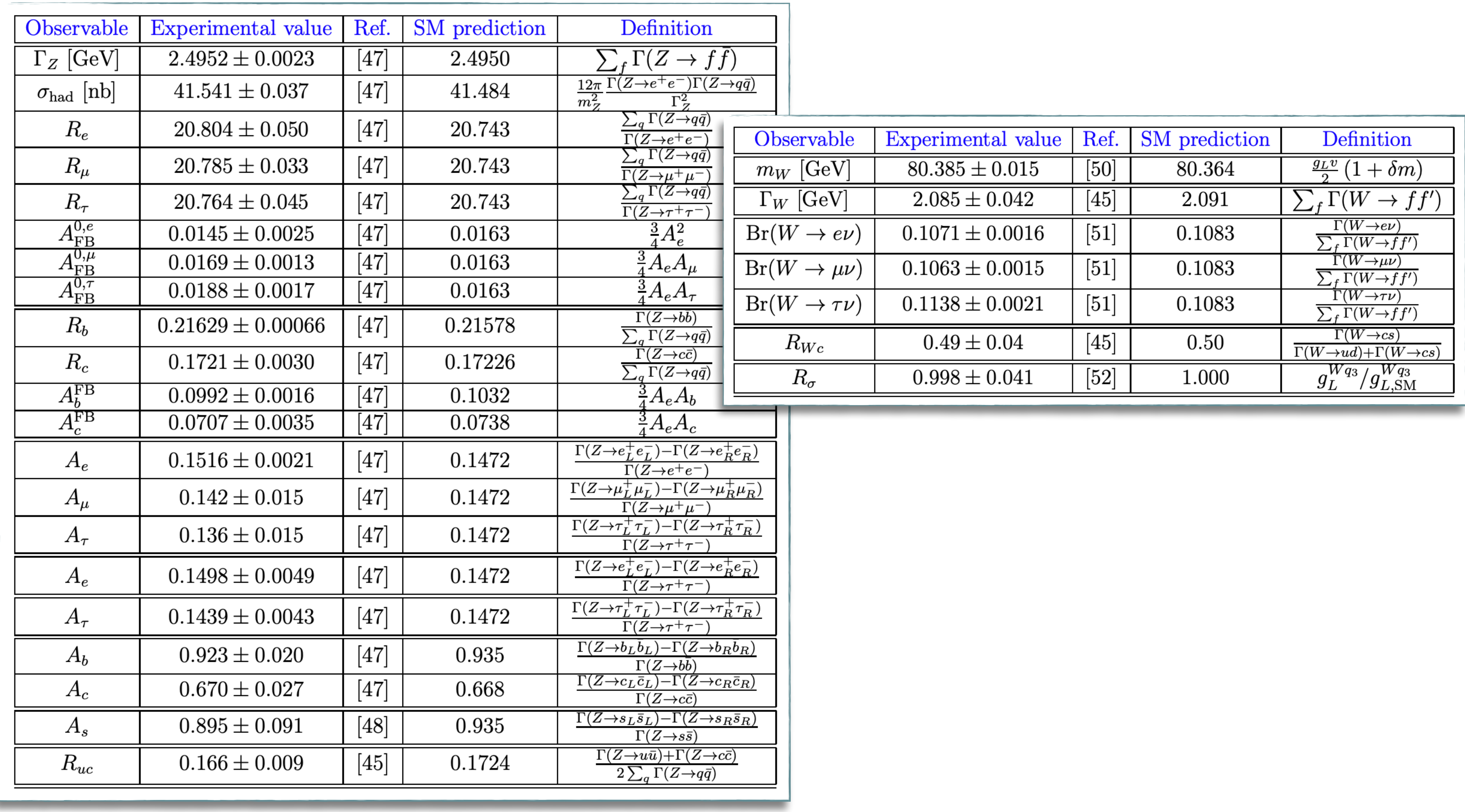
- *Low-energy observables* Falkowski et al. [1706.03783]



Class	Observable	Exp. value	Ref. & Comments	SM value
$\nu_e \nu_e qq$	$R_{\nu_e \bar{\nu}_e}$	0.41(14)	CHARM [73]	0.33
$\nu_\mu \nu_\mu qq$	$(g_L^{\nu_\mu})^2$	0.3005(28)	PDG [61], $\rho \approx 1$	0.3034
	$(g_R^{\nu_\mu})^2$	0.0329(30)		0.0302
	$\theta_L^{\nu_\mu}$	2.500(35)		2.4631
	$\theta_R^{\nu_\mu}$	$4.56^{+0.42}_{-0.27}$		5.1765
PV low-E $eeqq$	$g_{AV}^{eu} + 2g_{AV}^{ed}$	0.489(5)	PDG [61], $\rho \neq 1$	0.4951
	$2g_{AV}^{eu} - g_{AV}^{ed}$	$-0.708(16)$		-0.7192
	$2g_{VA}^{eu} - g_{VA}^{ed}$	$-0.144(68)$		-0.0949
	$g_{VA}^{eu} - g_{VA}^{ed}$	$-0.042(57)$ $-0.120(74)$	SAMPLE [89]	-0.0627
PV low-E $\mu\mu qq$	$b_{\rm SPS}(\lambda = 0.81)$	$-1.47(42) \cdot 10^{-4}$	SPS [90]	$-1.56 \cdot 10^{-4}$
	$b_{\rm SPS}(\lambda = 0.66)$	$-1.74(81) \cdot 10^{-4}$		$-1.57 \cdot 10^{-4}$
$d(s) \to u \ell \nu$	$\epsilon_i^{dj\ell}$	Eq. (3.17)	Ref. [55]	0
$e^+e^- \to q\bar{q}$	$\sigma(q\bar{q})$	$f(\sqrt{s})$	LEPEWWG [91], $\rho \neq 1$	$f(\sqrt{s})$
	σ_c, σ_b		LEPEWWG [100], VENUS [93], TOPAZ [94]	
	A_{FB}^{cc}, A_{FB}^{bb}			
$\nu_\mu \nu_\mu ee$	$g_{LV}^{\nu_\mu e}$	$-0.040(15)$	PDG [61], $\rho \neq 1$	-0.0396
	$g_{LA}^{\nu_\mu e}$	$-0.507(14)$		-0.5064
$e^-e^- \to e^-e^-$	g_{AV}^{ee}	0.0190(27)	PDG [61]	0.0225
$\nu_\mu \gamma^* \to \nu_\mu \mu^+ \mu^-$	$\frac{\sigma}{\sigma_{\rm SM}}$	1.58(57) 0.82(28)	CHARM [97] CCFR [98]	1
$\tau \to \ell \nu \nu$	$G_{\tau e}^2 / G_F^2$	1.0029(46)	PDG [61], $\rho \approx 1$	1
	$G_{\tau \mu}^2 / G_F^2$	0.981(18)		1
$e^+e^- \to \ell^+ \ell^-$	$\frac{d\sigma(ee)}{d\cos\theta}$	$f(\sqrt{s})$	LEPEWWG [91], $\rho \approx 1$	$f(\sqrt{s})$
	$\sigma_\mu, \sigma_\tau, \mathcal{P}_\tau$		LEPEWWG [100], VENUS [96]	
	A_{FB}^μ, A_{FB}^τ			

PREVIOUS GLOBAL ANALYSES

- *Pole observables* Efrati et al. [1503.07872]



Observable	Experimental value	Ref.	SM prediction	Definition
Γ_Z [GeV]	2.4952 ± 0.0023	[47]	2.4950	$\sum_f \Gamma(Z \to f\bar{f})$
$\sigma_{\rm had}$ [nb]	41.541 ± 0.037	[47]	41.484	$\frac{12\pi}{m_Z^2}\frac{\Gamma(Z\to e^+e^-)\Gamma(Z\to q\bar{q})}{\Gamma_Z^2}$
R_e	20.804 ± 0.050	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to e^+e^-)}$
R_μ	20.785 ± 0.033	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \mu^+\mu^-)}$
R_τ	20.764 ± 0.045	[47]	20.743	$\frac{\sum_q \Gamma(Z\to q\bar{q})}{\Gamma(Z\to \tau^+\tau^-)}$
$A_{\rm FB}^{0,e}$	0.0145 ± 0.0025	[47]	0.0163	$\frac{3}{4}A_e^2$
$A_{\rm FB}^{0,\mu}$	0.0169 ± 0.0013	[47]	0.0163	$\frac{3}{4}A_e A_\mu$
$A_{\rm FB}^{0,\tau}$	0.0188 ± 0.0017	[47]	0.0163	$\frac{3}{4}A_e A_\tau$
R_b	0.21629 ± 0.00066	[47]	0.21578	$\frac{\Gamma(Z\to b\bar{b})}{\sum_q \Gamma(Z\to q\bar{q})}$
R_c	0.1721 ± 0.0030	[47]	0.17226	$\frac{\Gamma(Z\to c\bar{c})}{\sum_q \Gamma(Z\to q\bar{q})}$
$A_b^{\rm FB}$	0.0992 ± 0.0016	[47]	0.1032	$\frac{3}{4}A_e A_b$
$A_c^{\rm FB}$	0.0707 ± 0.0035	[47]	0.0738	$\frac{3}{4}A_e A_c$
A_e	0.1516 ± 0.0021	[47]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to e^+e^-)}$
A_μ	0.142 ± 0.015	[47]	0.1472	$\frac{\Gamma(Z\to \mu_L^+\mu_L^-)-\Gamma(Z\to \mu_R^+\mu_R^-)}{\Gamma(Z\to \mu^+\mu^-)}$
A_τ	0.136 ± 0.015	[47]	0.1472	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_e	0.1498 ± 0.0049	[47]	0.1472	$\frac{\Gamma(Z\to e_L^+e_L^-)-\Gamma(Z\to e_R^+e_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_τ	0.1439 ± 0.0043	[47]	0.1472	$\frac{\Gamma(Z\to \tau_L^+\tau_L^-)-\Gamma(Z\to \tau_R^+\tau_R^-)}{\Gamma(Z\to \tau^+\tau^-)}$
A_b	0.923 ± 0.020	[47]	0.935	$\frac{\Gamma(Z\to b_L\bar{b}_L)-\Gamma(Z\to b_R\bar{b}_R)}{\Gamma(Z\to b\bar{b})}$
A_c	0.670 ± 0.027	[47]	0.668	$\frac{\Gamma(Z\to c_L\bar{c}_L)-\Gamma(Z\to c_R\bar{c}_R)}{\Gamma(Z\to c\bar{c})}$
A_s	0.895 ± 0.091	[48]	0.935	$\frac{\Gamma(Z\to s_L\bar{s}_L)-\Gamma(Z\to s_R\bar{s}_R)}{\Gamma(Z\to s\bar{s})}$
R_{uc}	0.166 ± 0.009	[45]	0.1724	$\frac{\Gamma(Z\to u\bar{u})+\Gamma(Z\to c\bar{c})}{2\sum_q \Gamma(Z\to q\bar{q})}$

Observable	Experimental value	Ref.	SM prediction	Definition
m_W [GeV]	80.385 ± 0.015	[50]	80.364	$\frac{g_L v}{2}(1+\delta m)$
Γ_W [GeV]	2.085 ± 0.042	[45]	2.091	$\sum_f \Gamma(W \to f f')$
$\mathrm{Br}(W \to e\nu)$	0.1071 ± 0.0016	[51]	0.1083	$\frac{\Gamma(W\to e\nu)}{\sum_f \Gamma(W\to f f')}$
$\mathrm{Br}(W \to \mu\nu)$	0.1063 ± 0.0015	[51]	0.1083	$\frac{\Gamma(W\to \mu\nu)}{\sum_f \Gamma(W\to f f')}$
$\mathrm{Br}(W \to \tau\nu)$	0.1138 ± 0.0021	[51]	0.1083	$\frac{\Gamma(W\to \tau\nu)}{\sum_f \Gamma(W\to f f')}$
R_{Wc}	0.49 ± 0.04	[45]	0.50	$\frac{\Gamma(W\to cs)}{\Gamma(W\to ud)+\Gamma(W\to cs)}$
R_σ	0.998 ± 0.041	[52]	1.000	$g_L^{W q_3}/g_{L,\rm SM}^{W q_3}$

TECHNICAL DETAILS — GF LFV

- 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—

NUCLEAR UNCERTAINTIES IN MU-E CONV

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

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

— Davidson et al [1810.01884] —

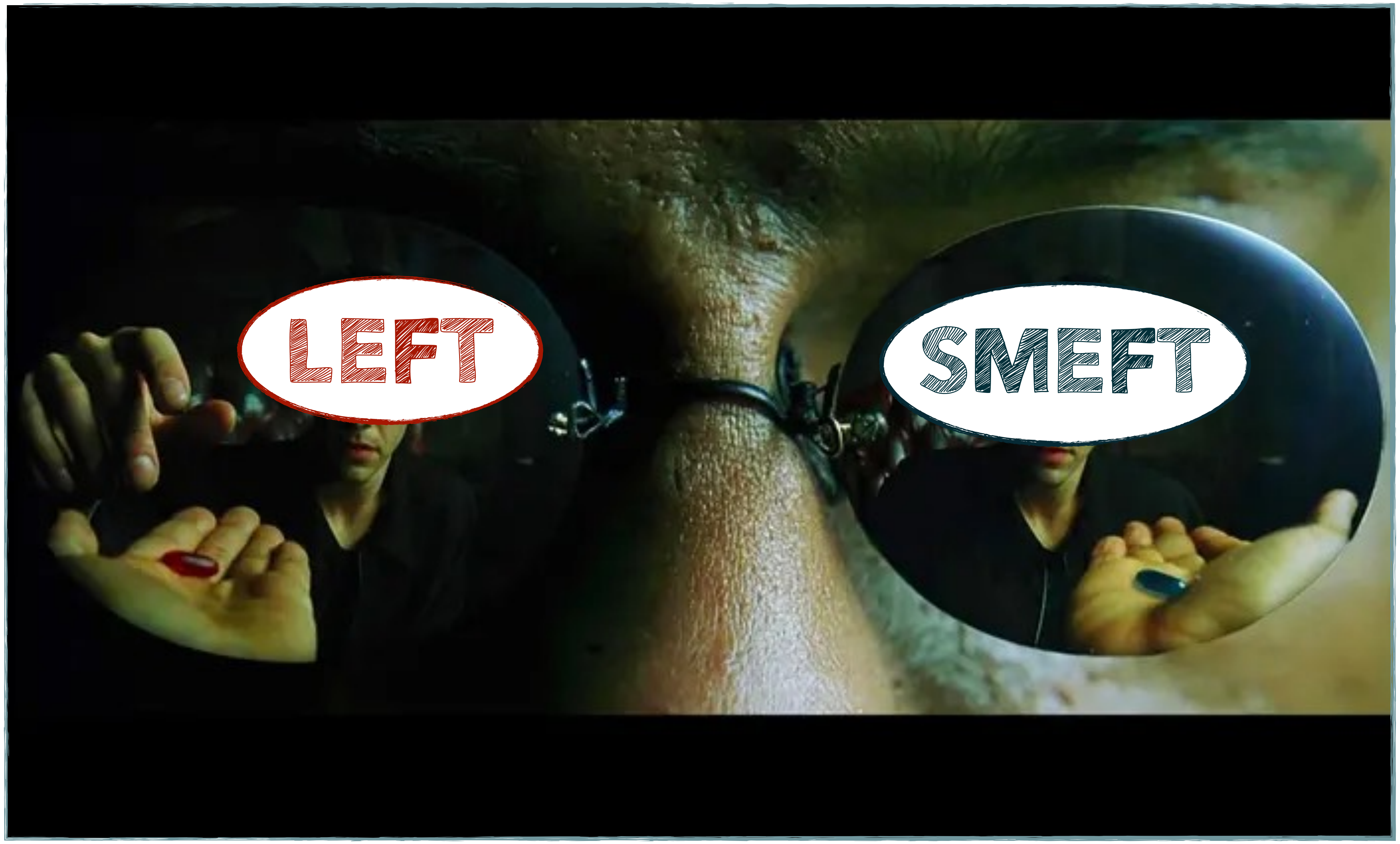
$$\left.\begin{array}{lcl} \mathrm{CR}(\mu \to e, \mathrm{S}) & < & 7.0 \times 10^{-11} \\ \mathrm{CR}(\mu \to e, \mathrm{Ti}) & < & 4.3 \times 10^{-12} \\ \mathrm{CR}(\mu \to e, \mathrm{Pb}) & < & 4.6 \times 10^{-11} \\ \mathrm{CR}(\mu \to e, \mathrm{Au}) & < & 7.0 \times 10^{-13} \end{array}\right\}$$

All independent bounds?

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

LOW-ENERGY EFT

WHEN LOOKING AT LOW-ENERGY PROCESSES



**There could also be a third option: HEFT*

Low and High Energy EFTs

energy

EW scale

e.g. cLFV obs

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

e.g. cLFV obs

LOW AND HIGH ENERGY EFTS

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

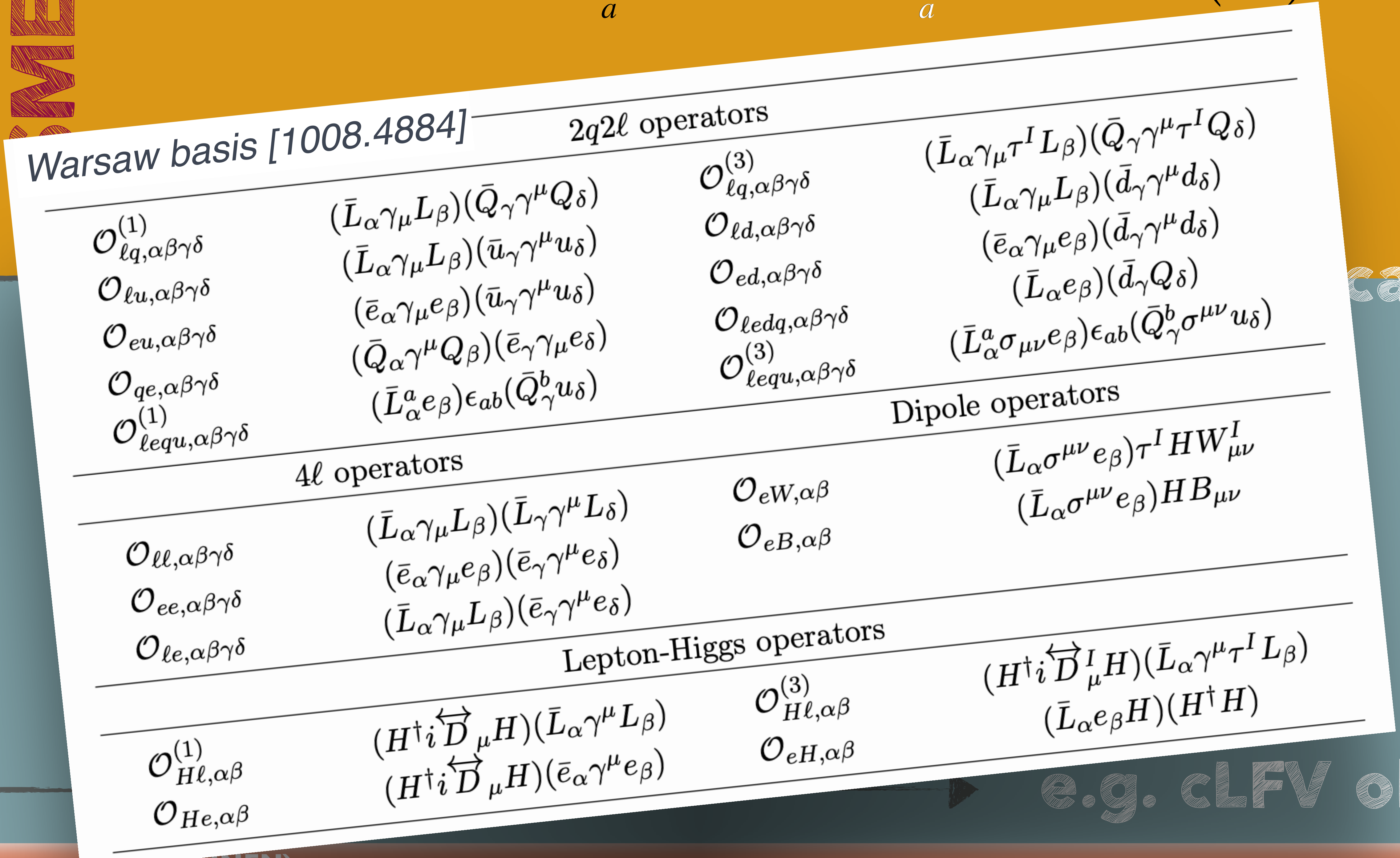
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \mathcal{O}\left(\frac{1}{\Lambda^3}\right)$$

energy

SMEFT

cale

e.g. 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

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

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

cLFV at dim-6

EW scale

LEFT

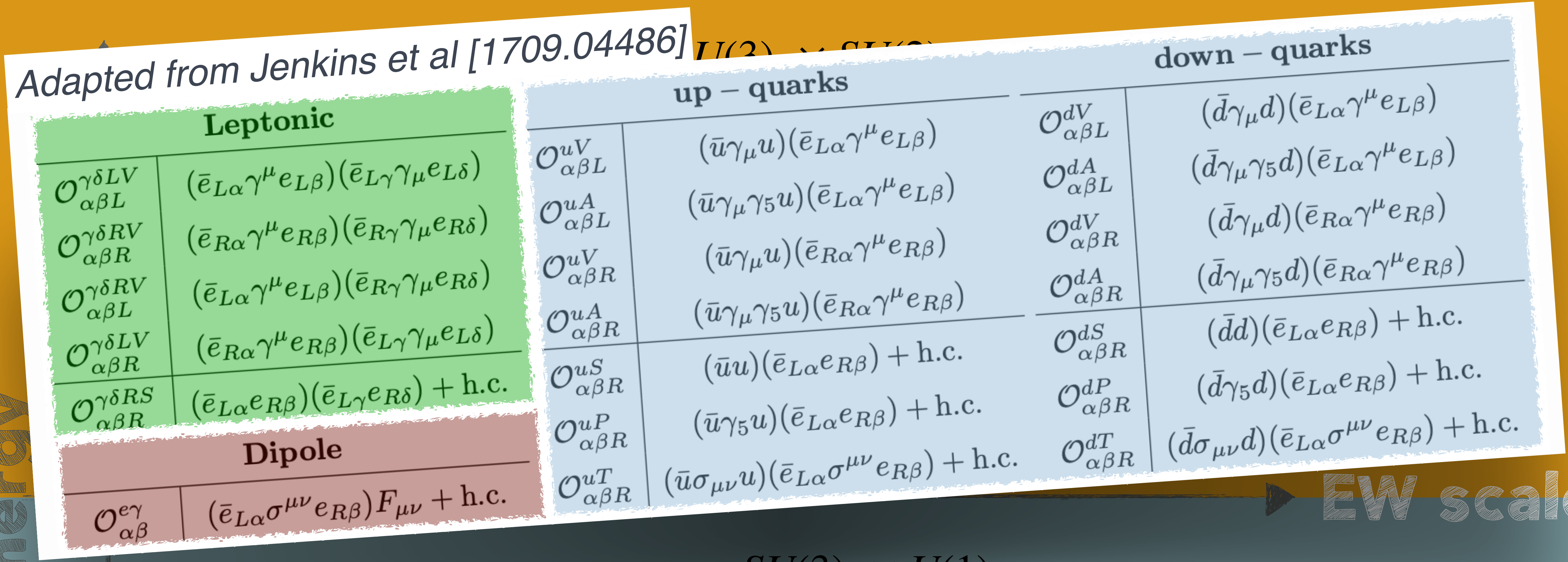
$$SU(3)_c \times U(1)_{EM}$$

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

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

e.g. cLFV obs

Low and High Energy EFTs



Adapted from Jenkins et al [1709.04486]

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

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

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

energy

EW scale

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

LEFT

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

← *dipole*

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

← *4-fermion*

e.g. cLFV obs

LOW AND HIGH ENERGY EFTS

SMEFT

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

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

cLFV at dim-6

EW scale

energy

LEFT

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

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

← ***dipole***

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

← ***4-fermion***

e.g. cLFV obs

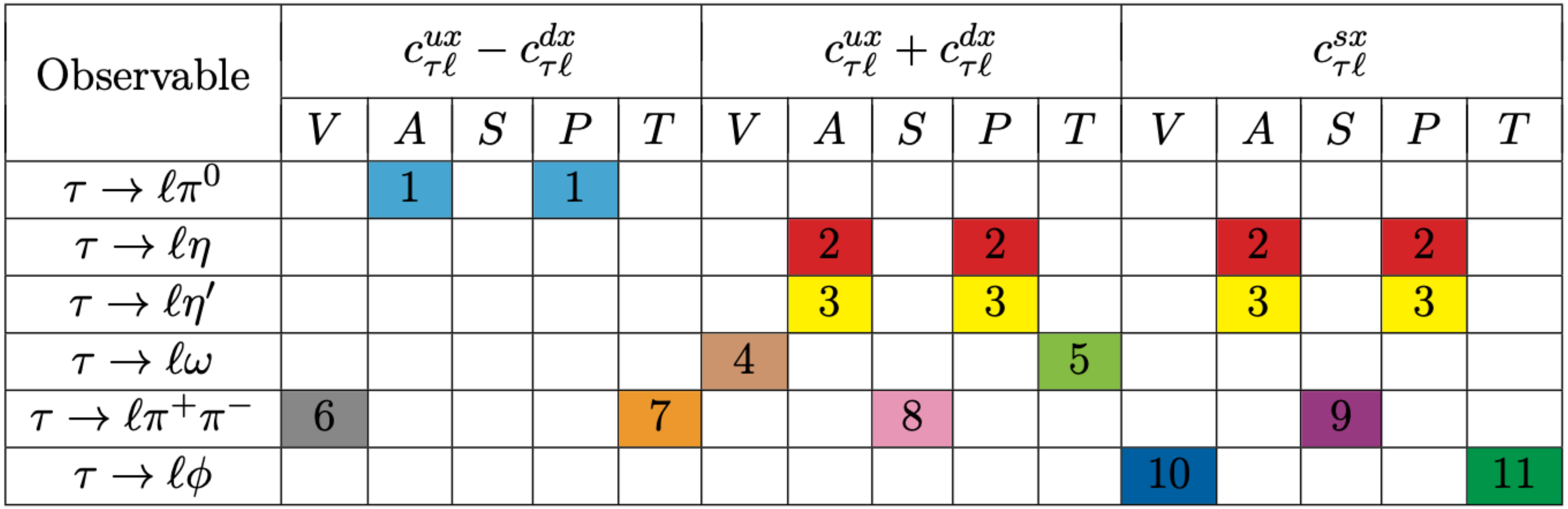
SEMILEPTONIC OPERATORS

- *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.:*

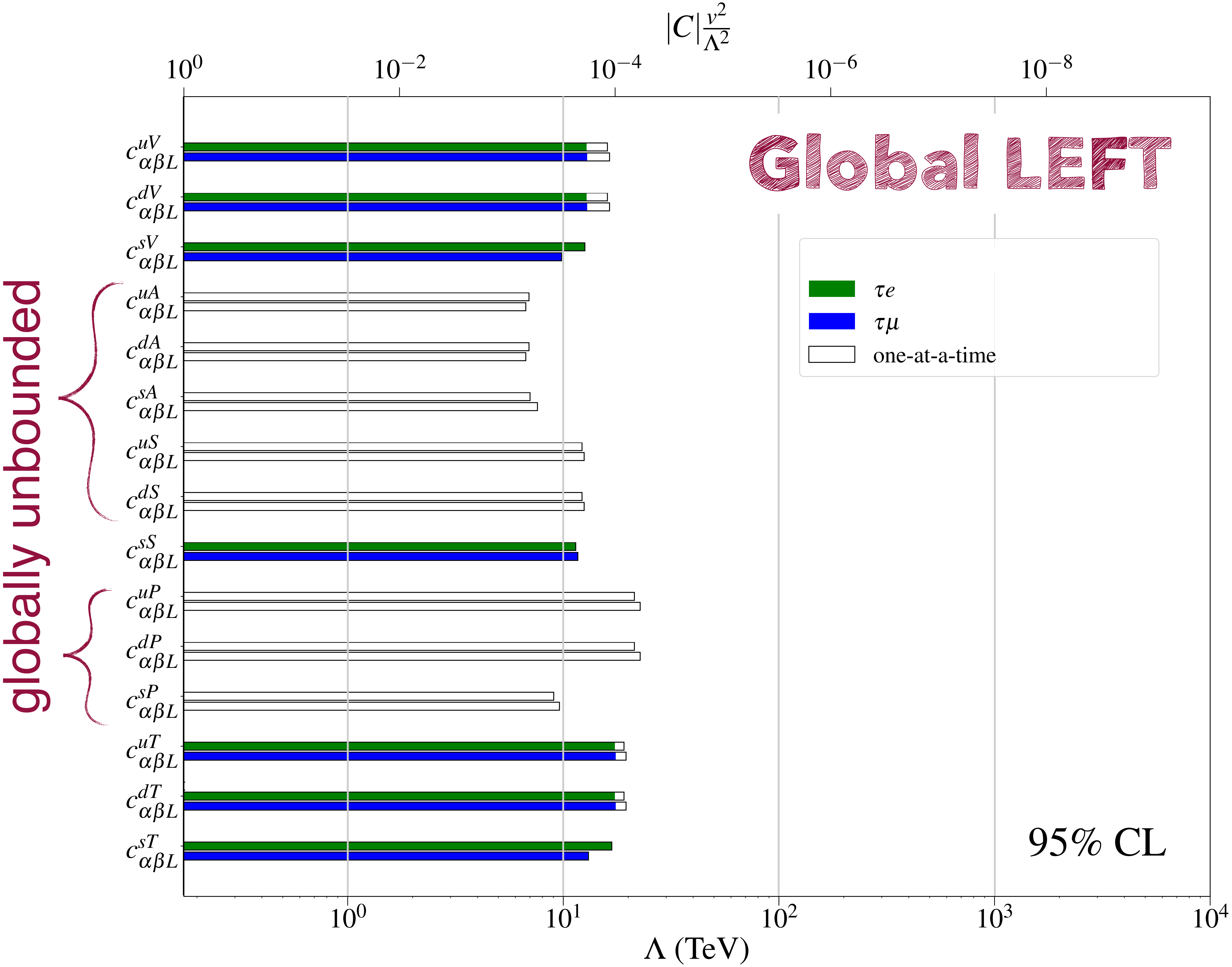


Observable	$c^{ux}_{\tau\ell} - c^{dx}_{\tau\ell}$					$c^{ux}_{\tau\ell} + c^{dx}_{\tau\ell}$					$c^{sx}_{\tau\ell}$				
	V	A	S	P	T	V	A	S	P	T	V	A	S	P	T
$\tau \to \ell\pi^0$		1		1											
$\tau \to \ell\eta$							2		2			2		2	
$\tau \to \ell\eta'$							3		3			3		3	
$\tau \to \ell\omega$						4	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

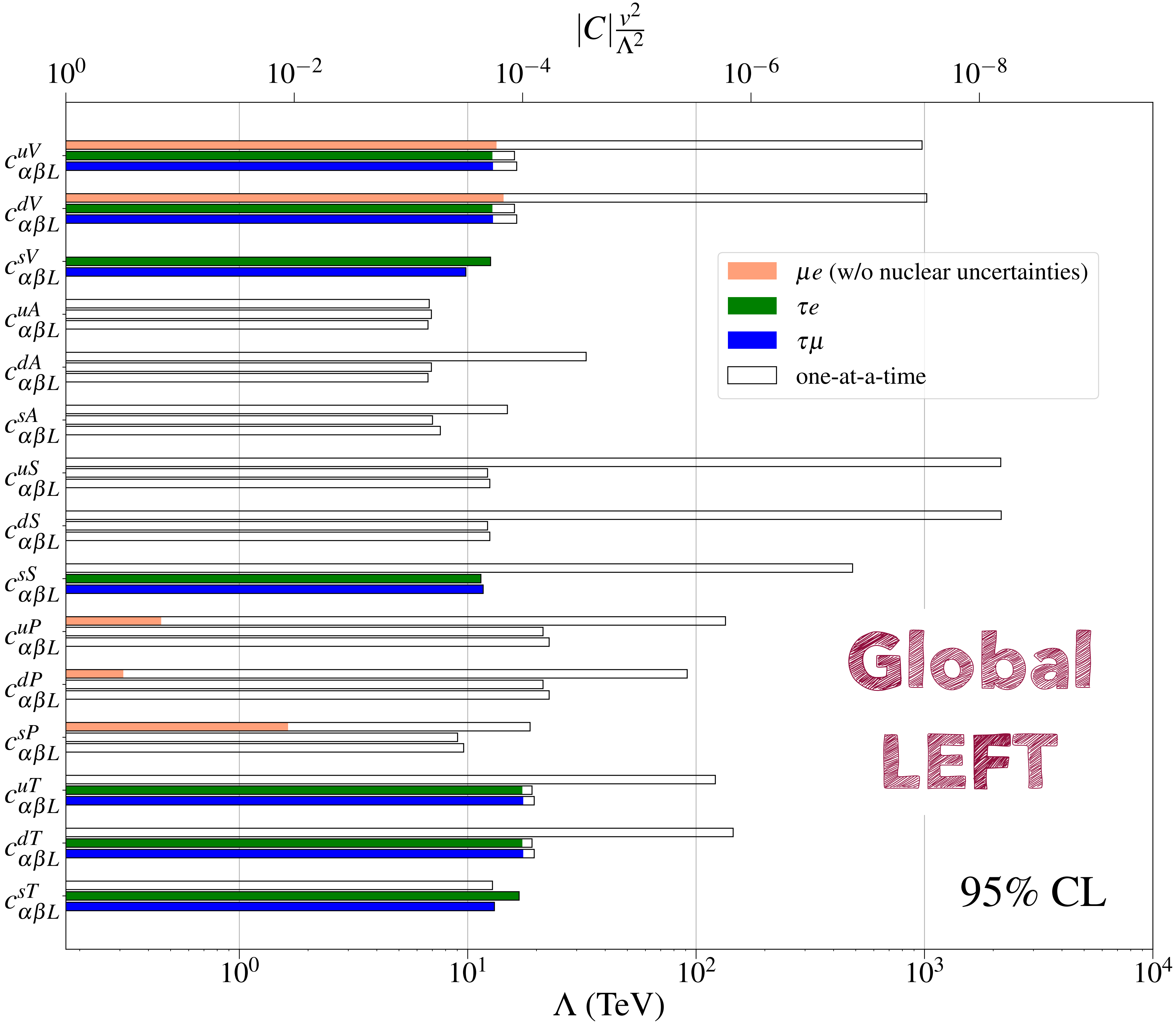
- *15 WCs - 11 indep. constraints = 4 flat directions*

— involving A, S and P WCs —

SEMILEPTONIC OPERATORS WITH TAUS



SEMILEPTONIC OPERATORS MU-E



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]—

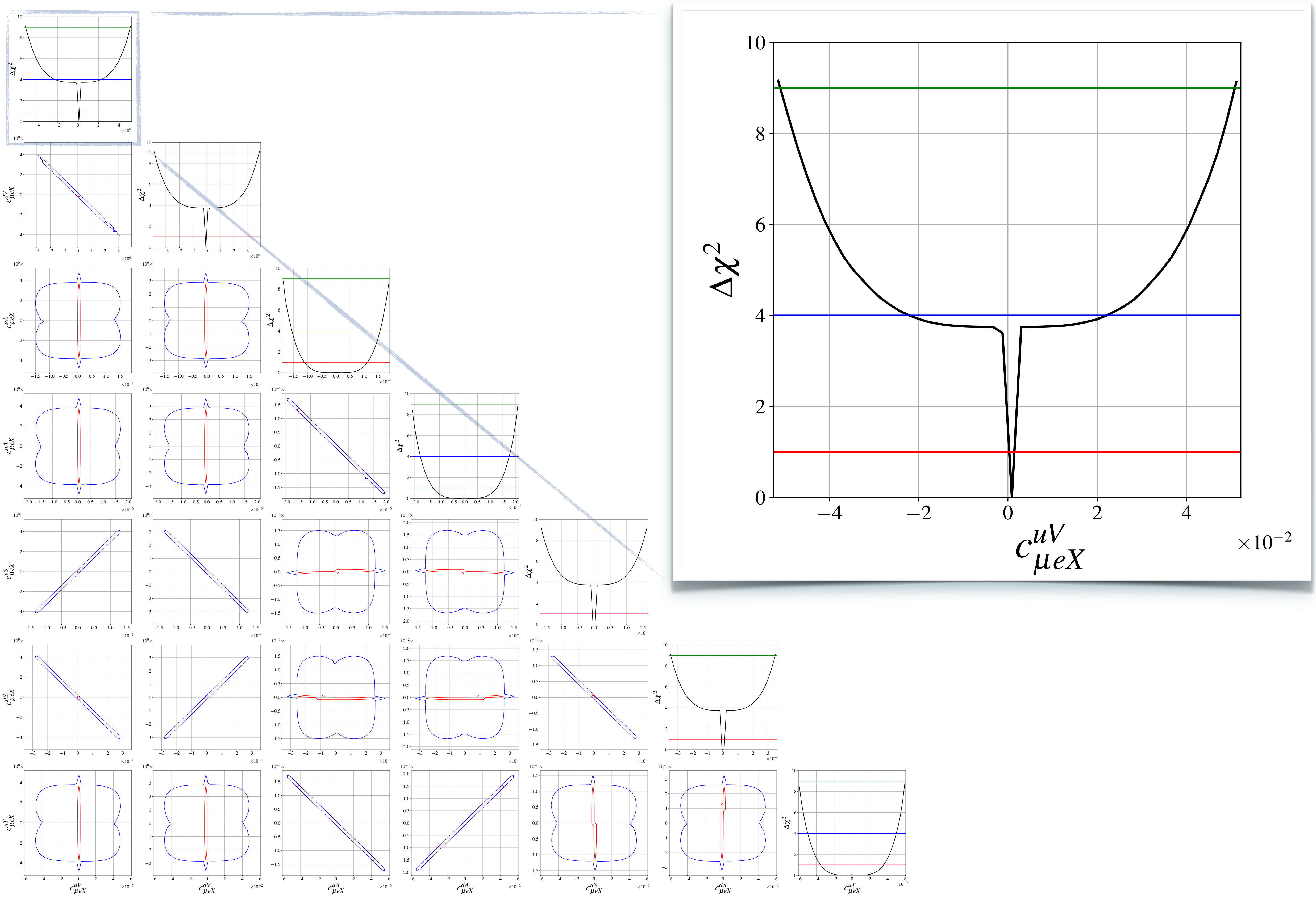
- *Nuclear corrections δ' and δ'' to the axial contribution of SD*

— Hoferichter et al [2204.06005]—

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

— Hoferichter et al [2204.06005]—

NUCLEAR UNCERTAINTIES



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]*—

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

— *Aebischer et al [1810.07698]*—

SEMILEPTONIC TAU DECAYS

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

$$\left. + \frac{h_\eta^u}{f_\pi m_\tau (m_u + m_d)}\left(c_{\tau\ell X}^{uP} + c_{\tau\ell X}^{dP}\right) + \frac{h_\eta^s}{2 f_\pi m_\tau m_s} c_{\tau\ell X}^{sP} \right|^2,$$

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

$$\left. + \frac{h_{\eta'}^u}{f_\pi m_\tau (m_u + m_d)}\left(c_{\tau\ell X}^{uP} + c_{\tau\ell X}^{dP}\right) + \frac{h_{\eta'}^s}{2 f_\pi m_\tau m_s} c_{\tau\ell X}^{sP} \right|^2.$$

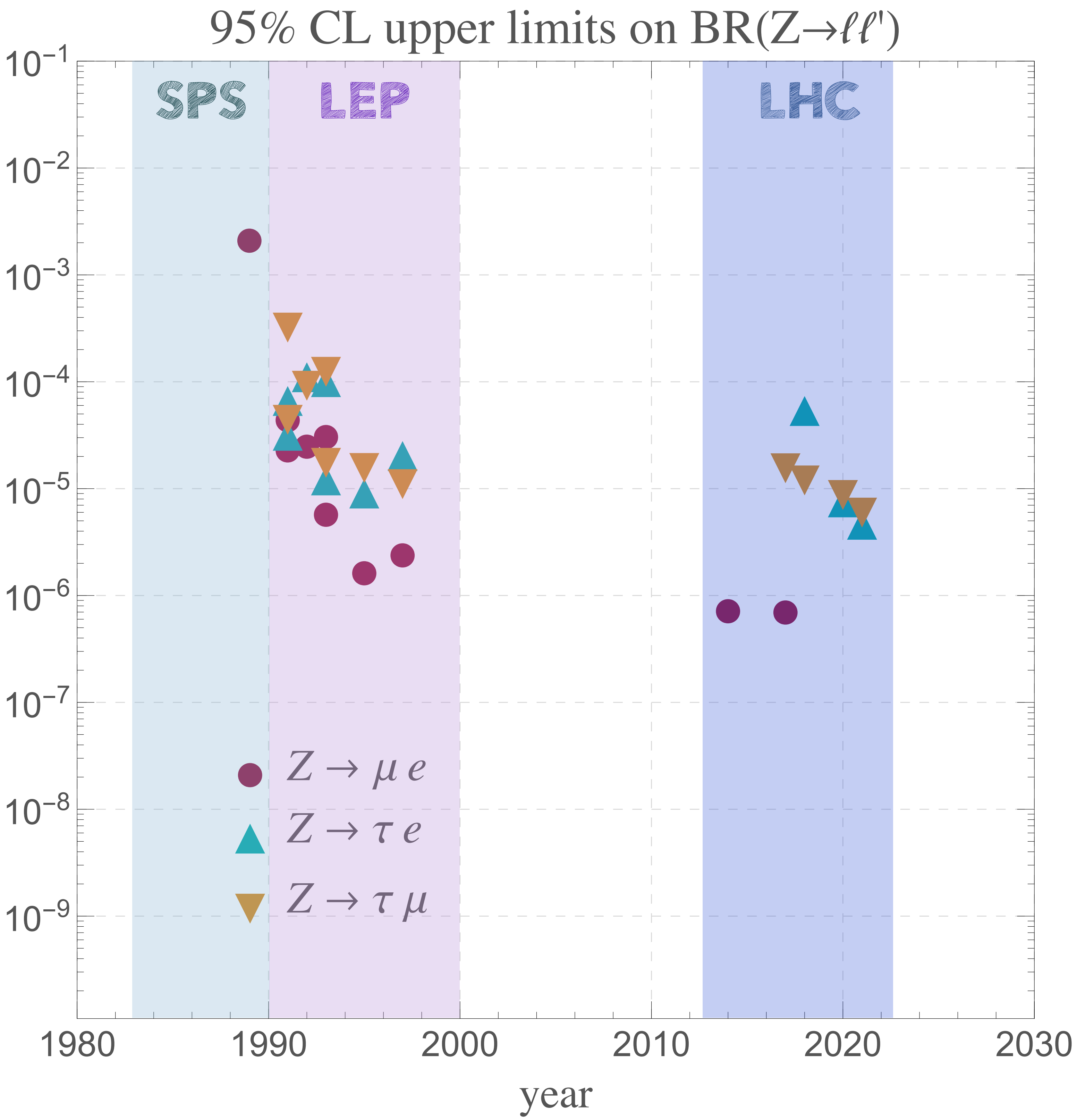
— Celis et al [1403.5781]—

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

$$\left. + 4\left(\frac{f_{T,\phi}}{f_\phi}\right)^2 \left(2\frac{m_\tau^2}{m_\phi^2} - 1 - \frac{m_\phi^2}{m_\tau^2}\right) \left|c_{\tau\ell X}^{sT}\right|^2 \right\},$$

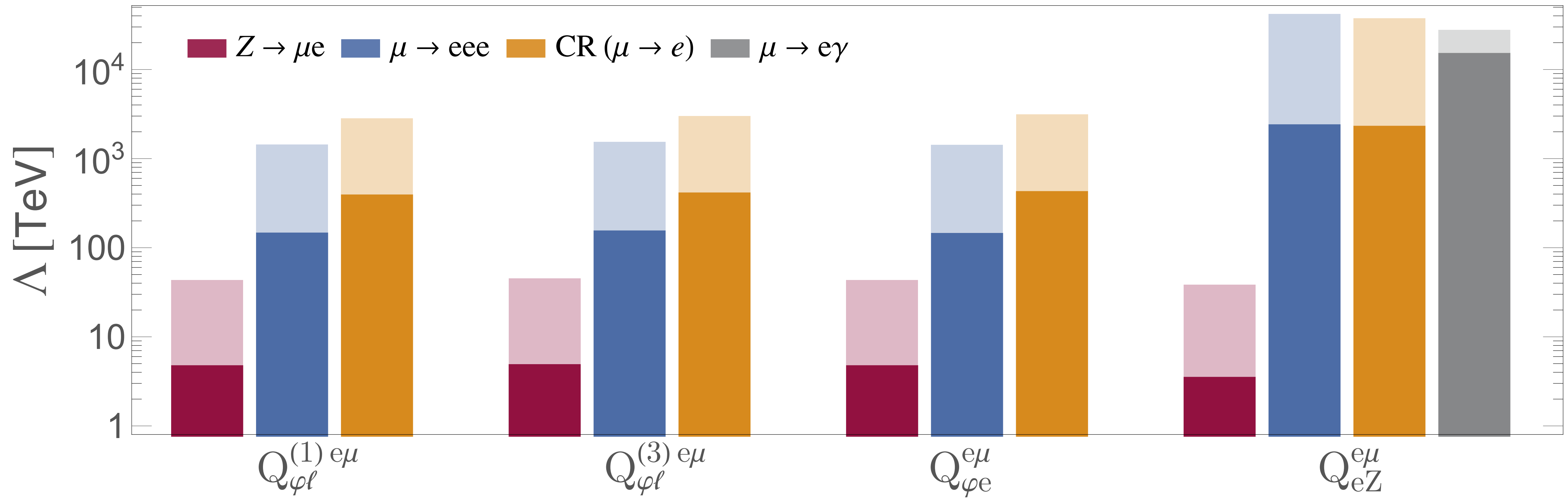
— Aebischer et al [1810.07698]—

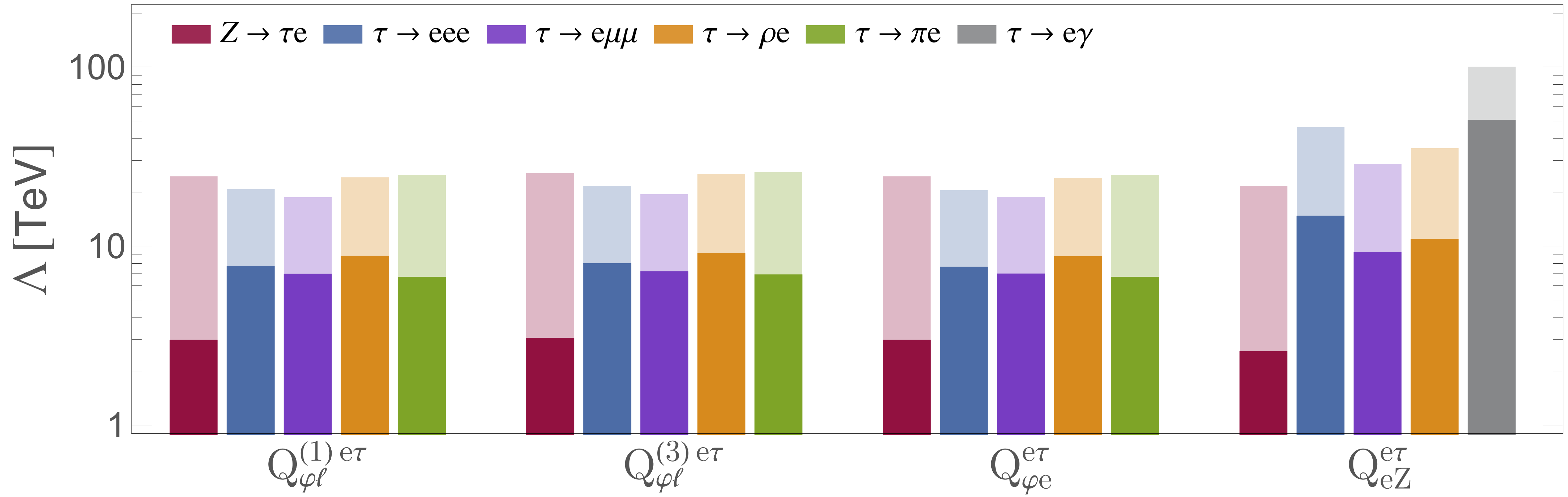
CLFV AT HIGH ENERGIES



LFV Z DECAYS

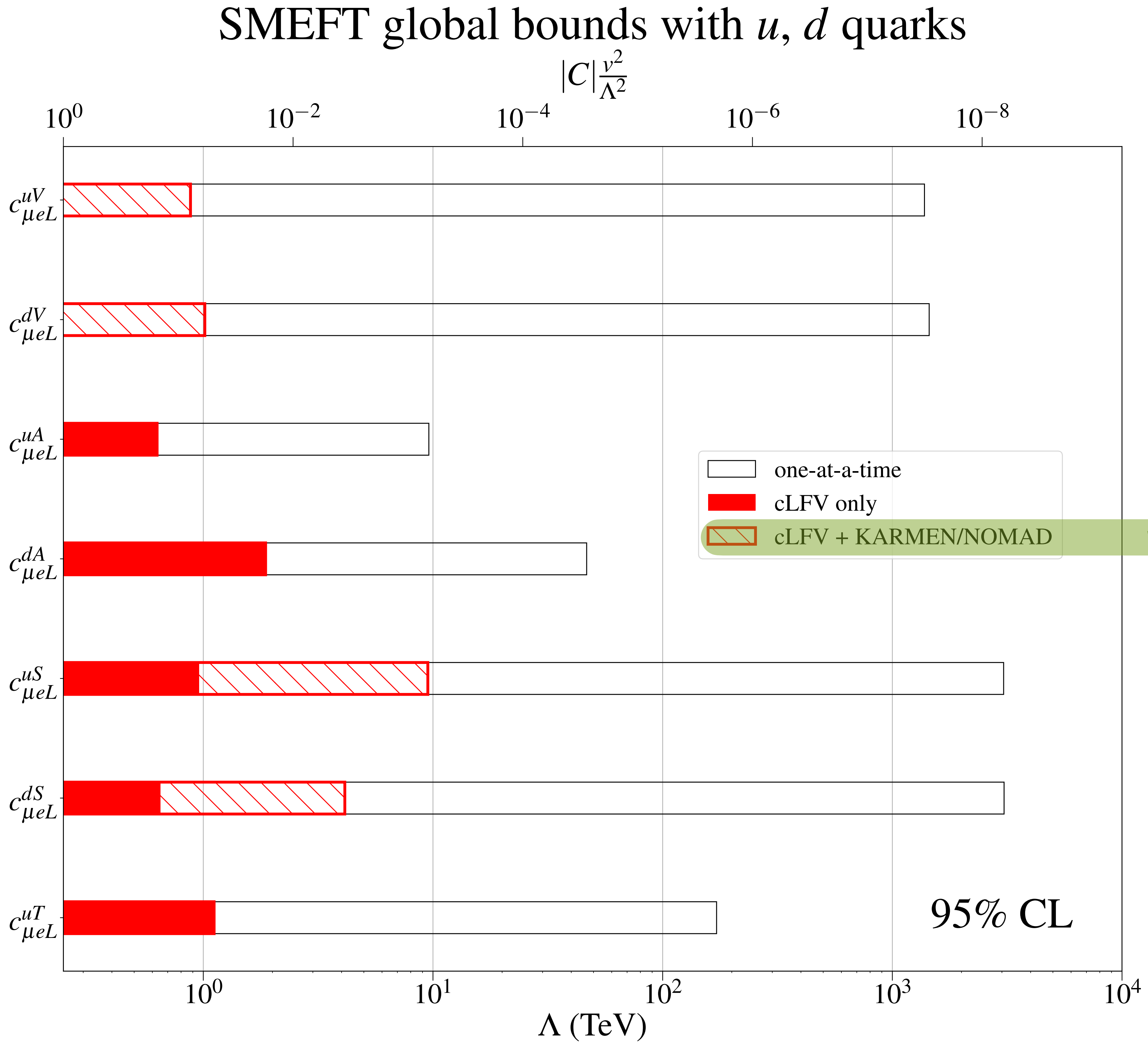
— *Calibbi, XM, Roy [2107.10273]* —





NEUTRINO INPUT FOR cLFV

Coloma, Fernández-Martínez, López-Pavón, XM, Naredo-Tuero, Urrea ***[2411.00090]***

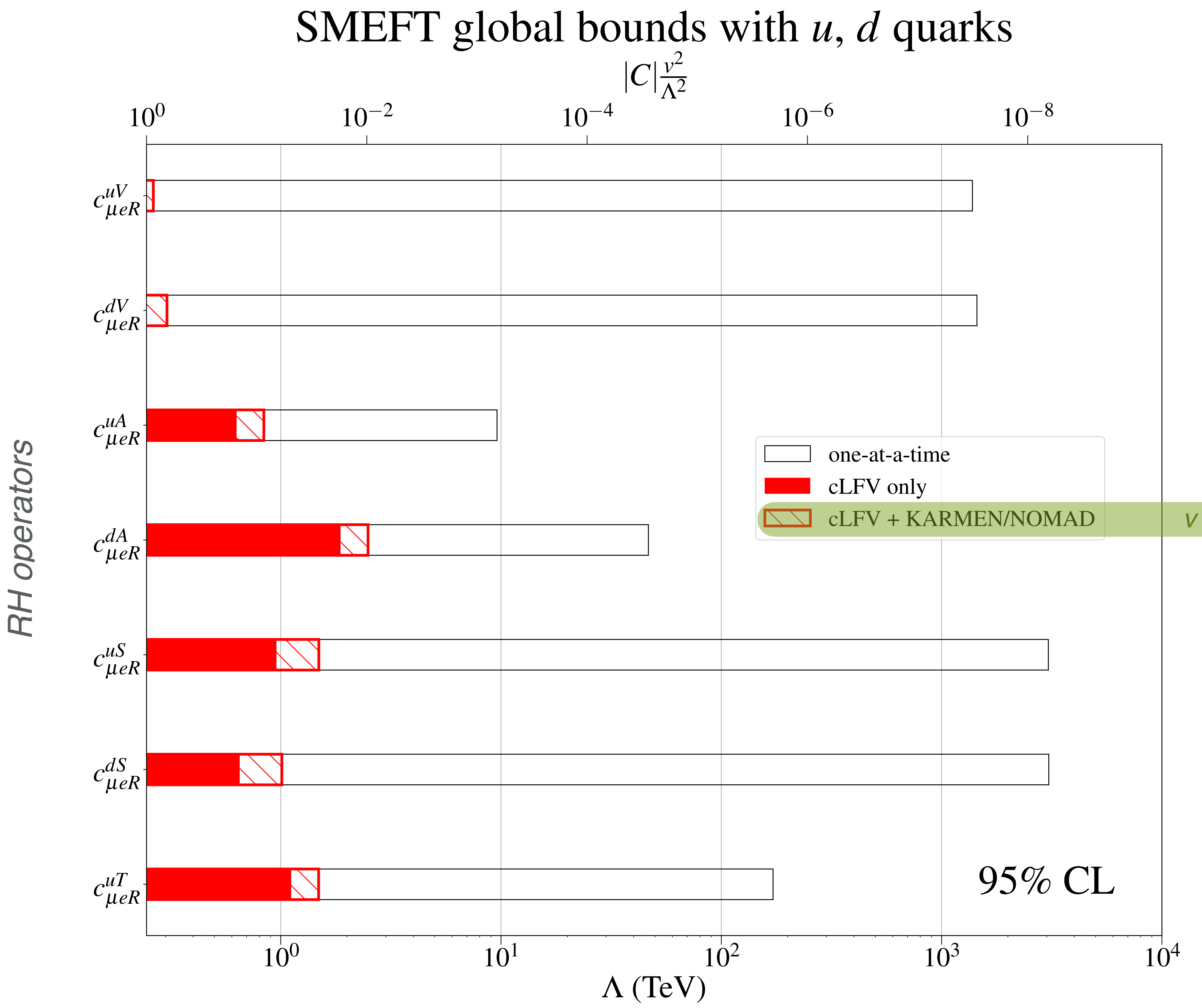


LH operators

ν osc at zero-distance

NEUTRINO INPUT FOR CLFV

Coloma, Fernández-Martínez, López-Pavón, XM, Naredo-Tuero, Urrea **[2411.00090]**



ν osc at zero-distance