Vectorlike Leptons in light of the Cabibbo-Angle Anomaly

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A.Crivellin, F.Kirk, C.A.M., M.Montull arXiv: 2008.01113

The Cabibbo-Angle Anomaly

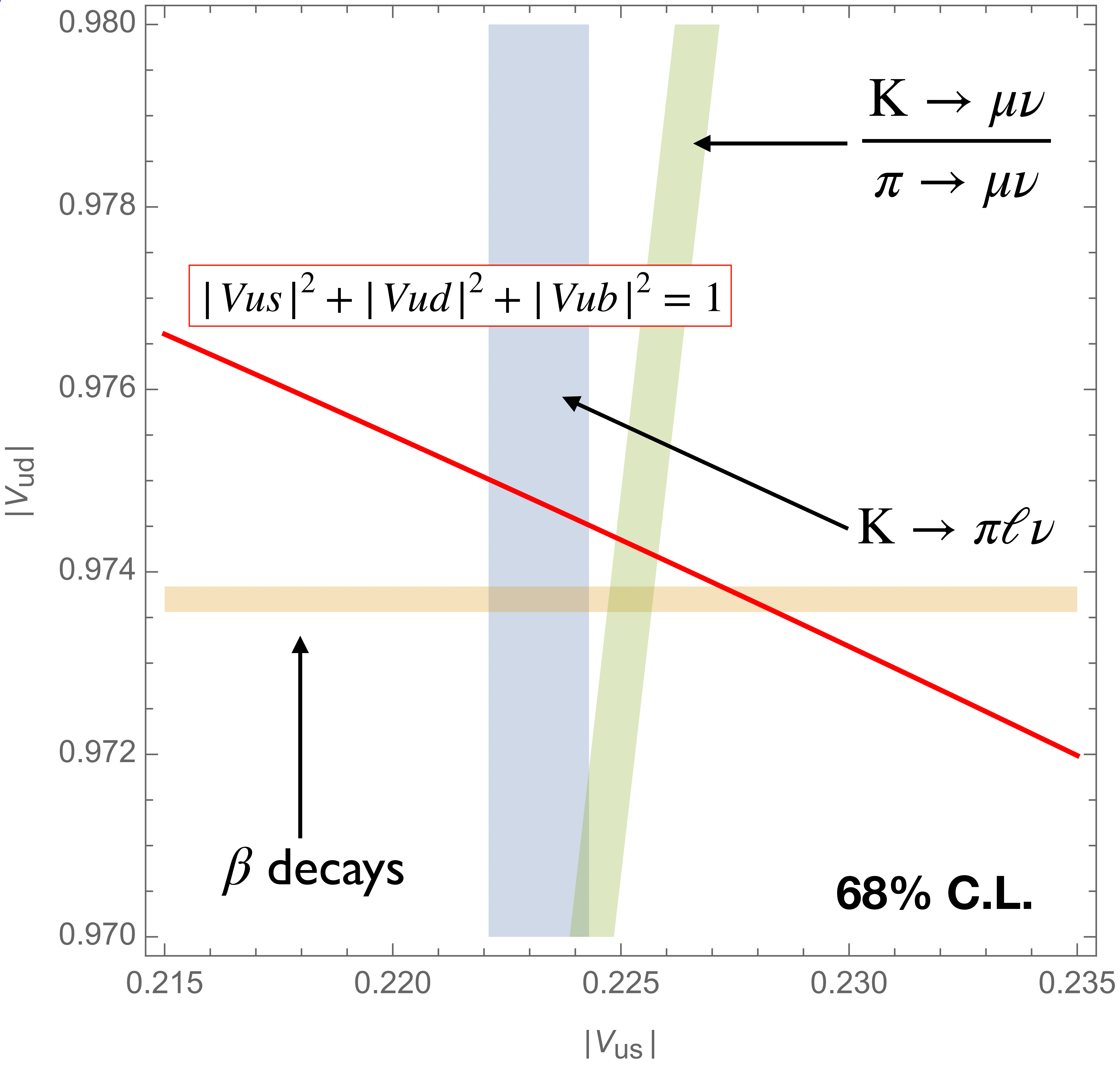
A DEFICIT IN THE FIRST ROW CKM UNITARITY RELATION

$$|V_{us}|^2 + |V_{ud}|^2 + |V_{ub}|^2 = 0.9985(5)$$

$$\left|\frac{V_{ud}}{V_{us}}\right|^2 \sim 20$$

≈ 0.0037
negligible error

?



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$$\left|\frac{V_{ud}}{V_{us}}\right|^2 \sim 20$$

≈ 0.0037
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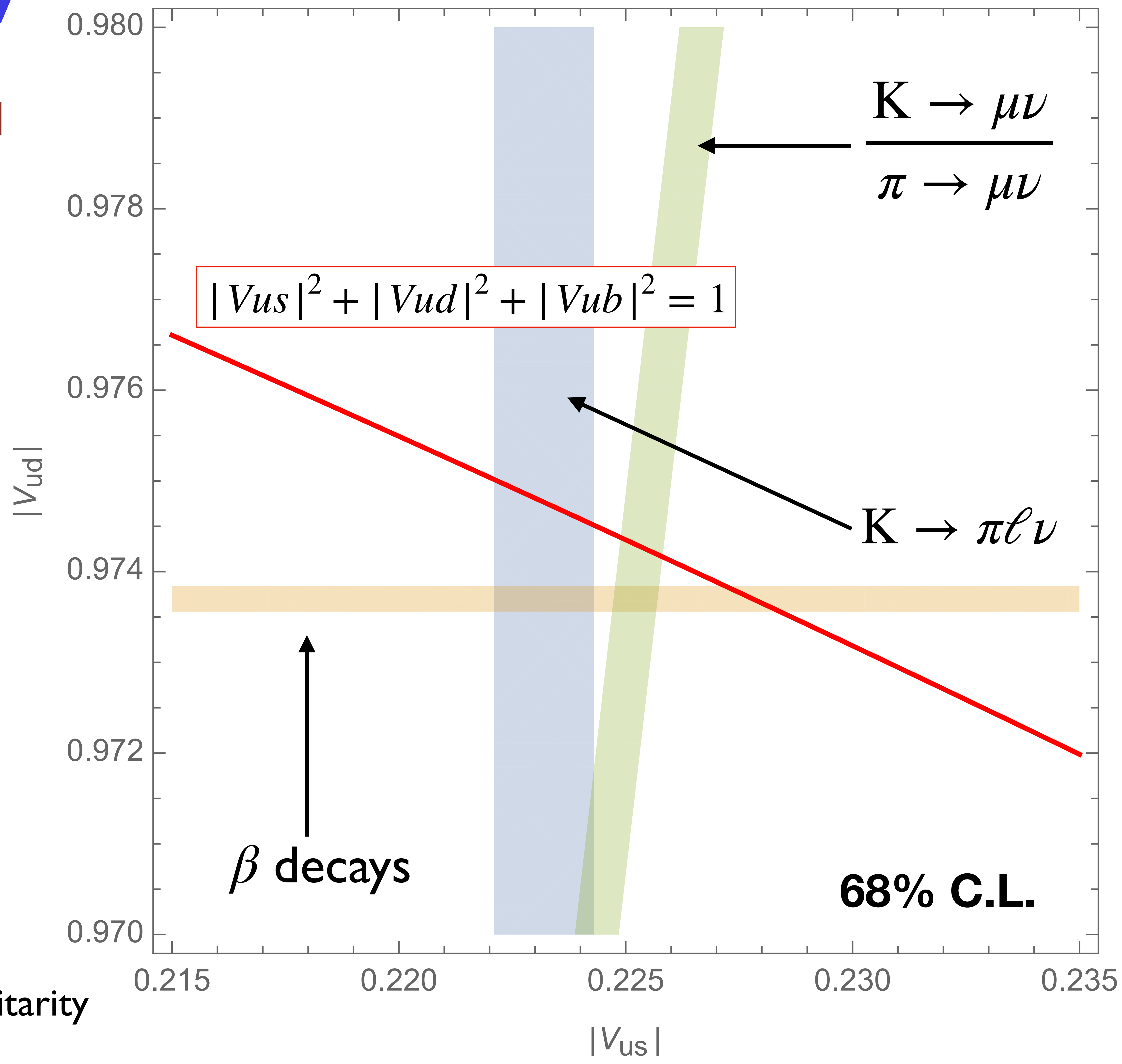
$$|V_{us}|^2 + |V_{ud}|^2(1-\varepsilon)^2 + |V_{ub}|^2 = 0.9985(5)$$



Note: there is also a (less significant) deficit in the first column of the CKM unitarity relation. This further strengthen the idea of a modification in V_{ud} from β decays.

EFT Approach

- **WE RECENTLY PROPOSED TO STUDY THIS ANOMALY AS A HINT OF LFUV** arXiv: 1912.08823 *A.Coutinho, A.Crivellin, C.A.M.*
- **MINIMAL APPROACH: CONSIDER OPERATORS WHICH MODIFY ONLY THE COUPLINGS OF W AND Z TO LEPTONS**
- **THERE ARE 3 OPERATORS AT THE DIM-6 LEVEL IN SMEFT**

$$Q_{\phi\ell}^{(1)ij} = \phi^\dagger i\overleftrightarrow{D}_\mu \phi \bar{\ell}^i \gamma^\mu \ell^j \qquad Q_{\phi\ell}^{(3)ij} = \phi^\dagger i\overleftrightarrow{D}^I_\mu \phi \bar{\ell}^i \tau^I \gamma^\mu \ell^j \qquad Q_{\phi e}^{ij} = \phi^\dagger i\overleftrightarrow{D}_\mu \phi \bar{e}^i \gamma^\mu e^j$$

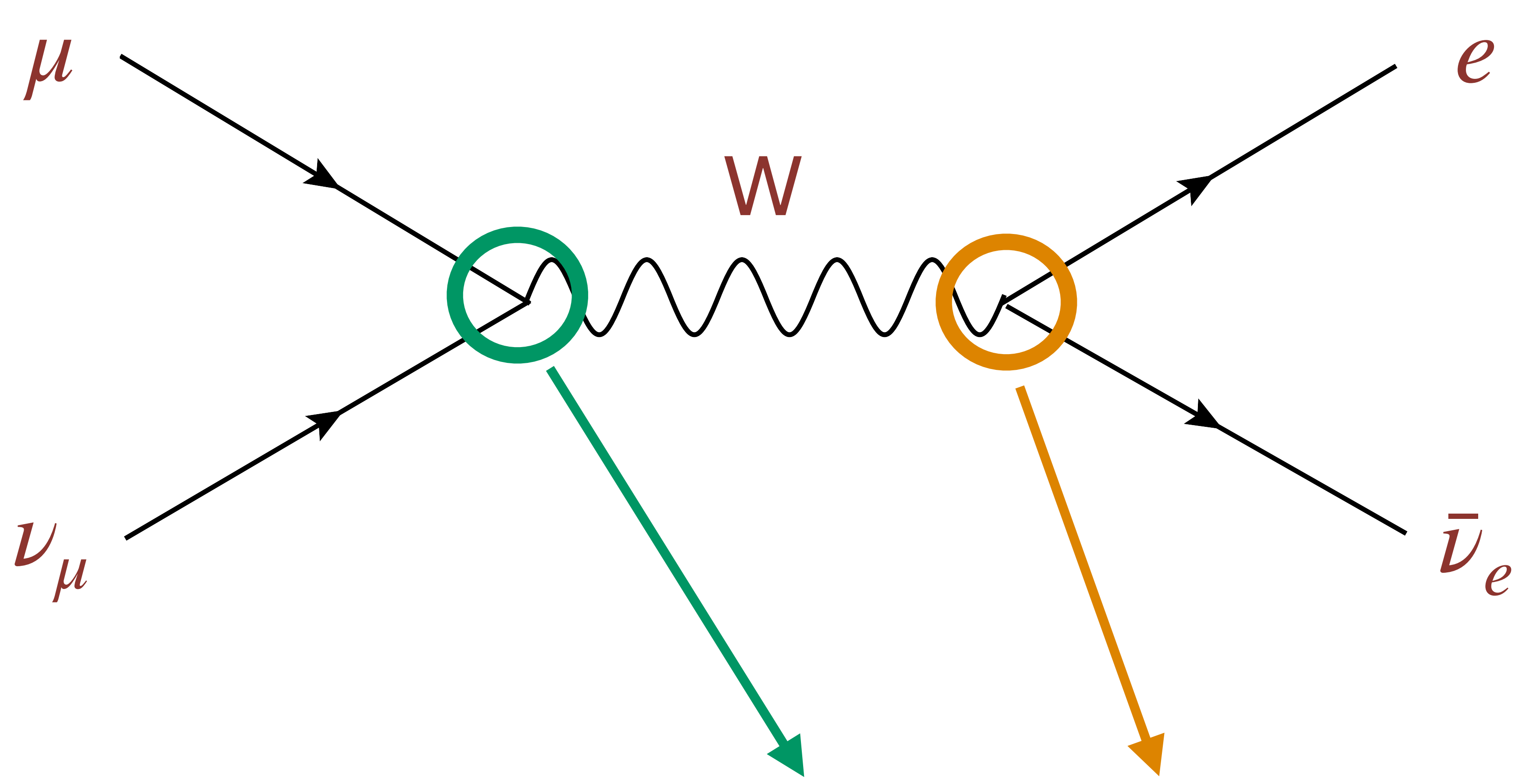
$$Z \to \ell\ell \propto C_{\phi\ell}^{(1)} + C_{\phi\ell}^{(3)} \qquad Z \to ee \propto C_{\phi e}$$

$$Z \to \nu\nu \propto C_{\phi\ell}^{(3)} - C_{\phi\ell}^{(1)} \qquad W \to \ell\nu \propto C_{\phi\ell}^{(3)}$$

EW Precision Observables

The EW sector can be parametrized by 3 Lagrangian parameters

$$\alpha \equiv \alpha^{\mathscr{L}} \qquad M_Z \equiv M_Z^{\mathscr{L}}$$



$$G_F = G_F^{\mathscr{L}}\left(1 + C_{\phi\ell}^{(3)\mu\mu} + C_{\phi\ell}^{(3)ee}\right)$$

induces very important indirect modifications in several observables

Observable	Measurement
M_W [GeV]	80.379(12)
Γ_W [GeV]	2.085(42)
$\mathrm{BR}(W \to \mathrm{had})$	0.6741(27)
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}(Q_{\mathrm{FB}}^{\mathrm{had}})$	0.2324(12)
$\sin^2\theta_{\mathrm{eff(Tev)}}^{\mathrm{lept}}$	0.23148(33)
$\sin^2\theta_{\mathrm{eff(LHC)}}^{\mathrm{lept}}$	0.23104(49)
P_τ^{pol}	0.1465(33)
A_ℓ	0.1513(21)
Γ_Z [GeV]	2.4952(23)
σ_h^0 [nb]	41.541(37)
R_ℓ^0	20.767(35)
$A_{\mathrm{FB}}^{0,\ell}$	0.0171(10)

The full list of observables can be found in: 2008.01113

LFU Tests

Violation of LFU in the charged current can be tested by ratios of W, K, π, τ decays, which have reduced theoretical and experimental uncertainties.

$$R(Y) = \frac{\mathscr{A}[Y]}{\mathscr{A}[Y]_{SM}}$$

Observable	Measurement
$R\left[\frac{K\to\mu\nu}{K\to e\nu}\right] \simeq \lvert 1 + \frac{v^2}{\Lambda^2} C_{\phi\ell}^{(3)\mu\mu} - \frac{v^2}{\Lambda^2} C_{\phi\ell}^{(3)ee} \rvert$	0.9978 ± 0.0020
$R\left[\frac{\pi\to\mu\nu}{\pi\to e\nu}\right] \simeq \lvert 1 + \frac{v^2}{\Lambda^2} C_{\phi\ell}^{(3)\mu\mu} - \frac{v^2}{\Lambda^2} C_{\phi\ell}^{(3)ee} \rvert$	1.0010 ± 0.0009
$R\left[\frac{\tau\to\mu\nu\bar{\nu}}{\tau\to e\nu\bar{\nu}}\right] \simeq \lvert 1 + \frac{v^2}{\Lambda^2} C_{\phi\ell}^{(3)\mu\mu} - \frac{v^2}{\Lambda^2} C_{\phi\ell}^{(3)ee} \rvert$	1.0018 ± 0.0014
$R\left[\frac{K\to\pi\mu\bar{\nu}}{K\to\pi e\bar{\nu}}\right] \simeq \lvert 1 + \frac{v^2}{\Lambda^2} C_{\phi\ell}^{(3)\mu\mu} - \frac{v^2}{\Lambda^2} C_{\phi\ell}^{(3)ee} \rvert$	1.0010 ± 0.0025
$R\left[\frac{W\to\mu\bar{\nu}}{W\to e\bar{\nu}}\right] \simeq \lvert 1 + \frac{v^2}{\Lambda^2} C_{\phi\ell}^{(3)\mu\mu} - \frac{v^2}{\Lambda^2} C_{\phi\ell}^{(3)ee} \rvert$	0.996 ± 0.010

The full list of observables can be found in: 2008.01113

CAA

Including direct and indirect effects (G_F):

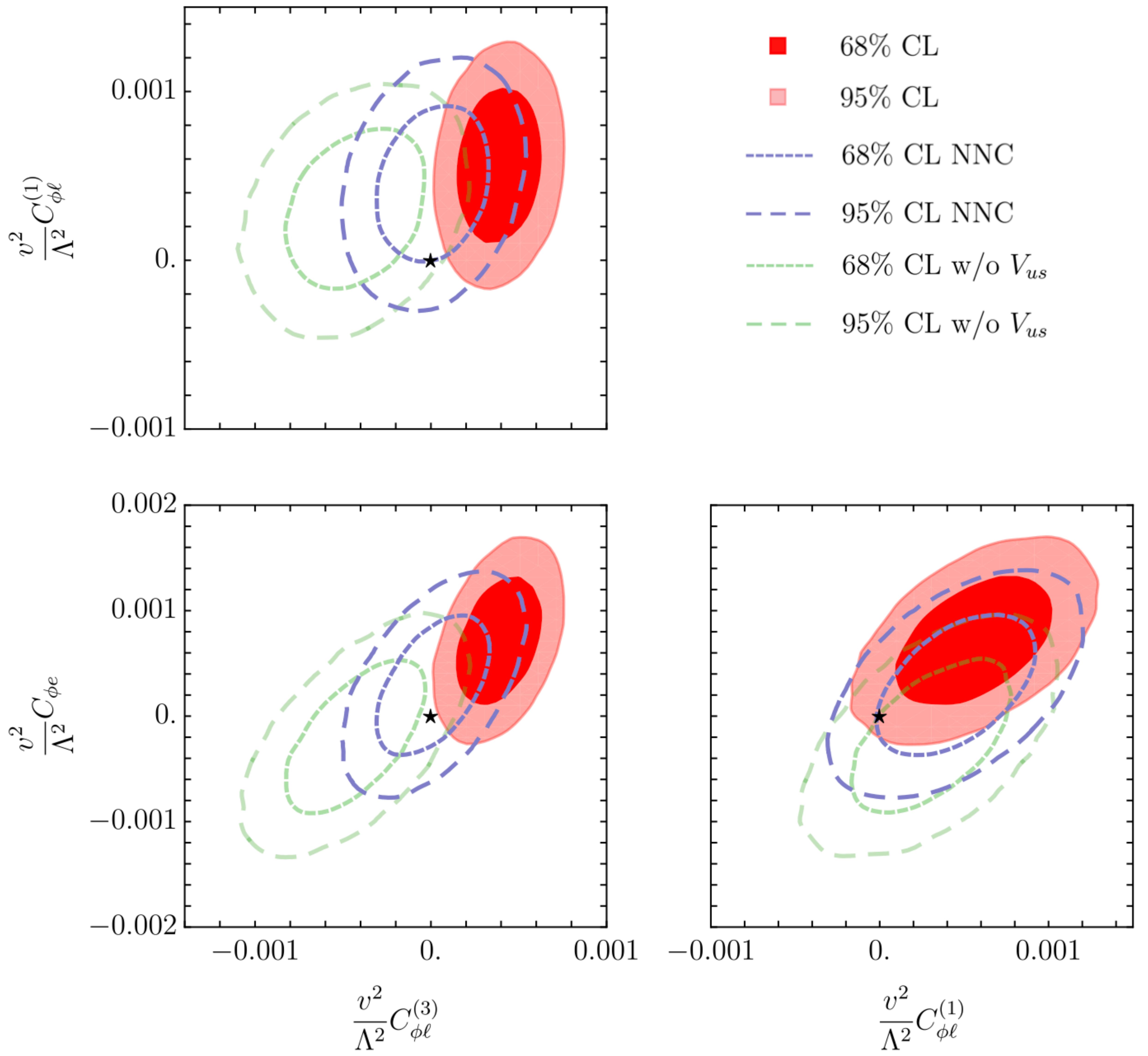
$$\left|V_{us}^{K_{\mu 3}}\right| \simeq \left|V_{us}^{\mathscr{L}}\left(1 - \frac{v^2}{\Lambda^2} C_{\phi\ell}^{(3)ee}\right)\right| \qquad \left|V_{ud}^{\beta}\right| \simeq \left|V_{ud}^{\mathscr{L}}\left(1 - \frac{v^2}{\Lambda^2} C_{\phi\ell}^{(3)\mu\mu}\right)\right|$$

EFT Analysis

LFU scenario: 3 NP parameters

- Significative impact of CAA due to $|V_{ud}^2/V_{us}^2|$ enhancement of $W\mu\nu$
- $C_{\phi e}$ compatibile with 0 (the same is found allowing LFUV)

	NP parameters	IC value ~
SM	0	93
LFUV	6	83
$C_{\phi\ell}^{(3)ii} = -C_{\phi\ell}^{(1)ii}$	3	76
$C_{\phi\ell}^{(3)}$ only	3	88



Vectorlike Leptons

- **VECTORLIKE LEPTONS ARE:**
  - Fermions
  - Vectorial under $SU(2)_L \times U(1)_Y$
  - Singlets under QCD
  - Couple to the SM Higgs and SM leptons via Yukawa-like couplings

$$\mathscr{L}^{\text{VLL}} = \sum_{\psi} i\bar{\psi}\gamma_\mu D^\mu \psi - M_\psi \bar{\psi}\psi$$

$$-\mathscr{L}^{\text{int}} = \lambda_N^i \bar{\ell}_i \tilde{\phi} N + \lambda_E^i \bar{\ell}_i \phi E + \lambda_{\Delta_1}^i \bar{\Delta}_1 \phi e_i + \lambda_{\Delta_3}^i \bar{\Delta}_3 \tilde{\phi} e_i$$
$$+\lambda_{\Sigma_0}^i \tilde{\phi}^\dagger \bar{\Sigma}_0^I \tau^I \ell_i + \lambda_{\Sigma_1}^i \phi^\dagger \bar{\Sigma}_1^I \tau^I \ell_i + h.c.$$

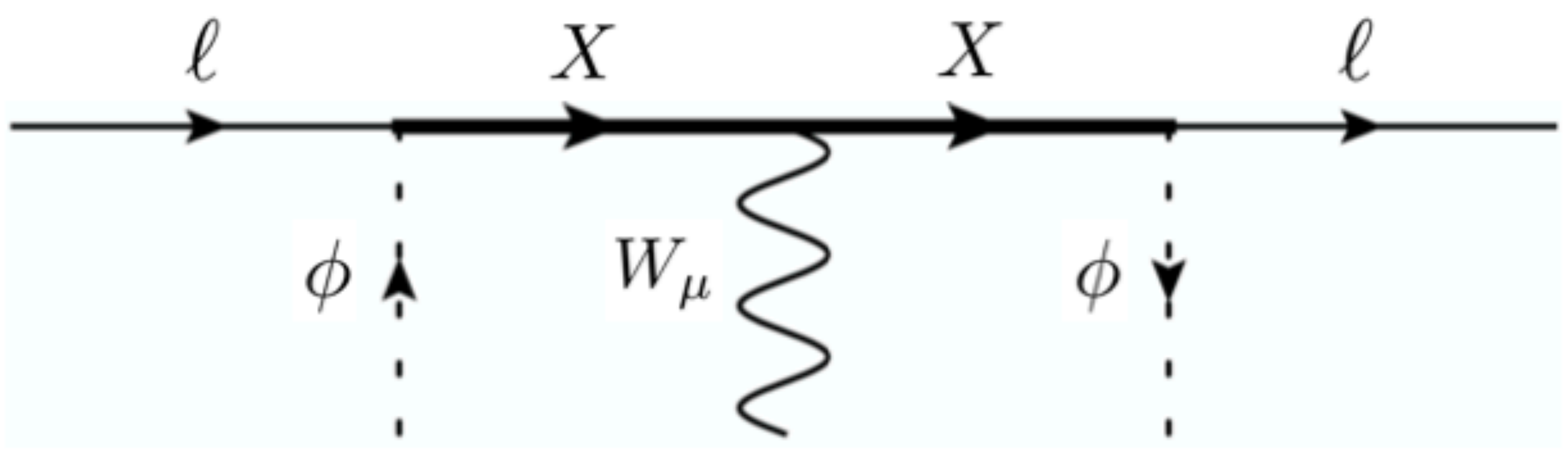
	$SU(3)$	$SU(2)_L$	$U(1)_Y$
ℓ	1	2	-1/2
e	1	1	-1
ϕ	1	2	1/2
N	1	1	0
E	1	1	-1
$\Delta_1 = (\Delta_1^0, \Delta_1^-)$	1	2	-1/2
$\Delta_3 = (\Delta_3^-, \Delta_3^{--})$	1	2	-3/2
$\Sigma_0 = (\Sigma_0^+, \Sigma_0^0, \Sigma_0^-)$	1	3	0
$\Sigma_1 = (\Sigma_1^0, \Sigma_1^-, \Sigma_1^{--})$	1	3	-1

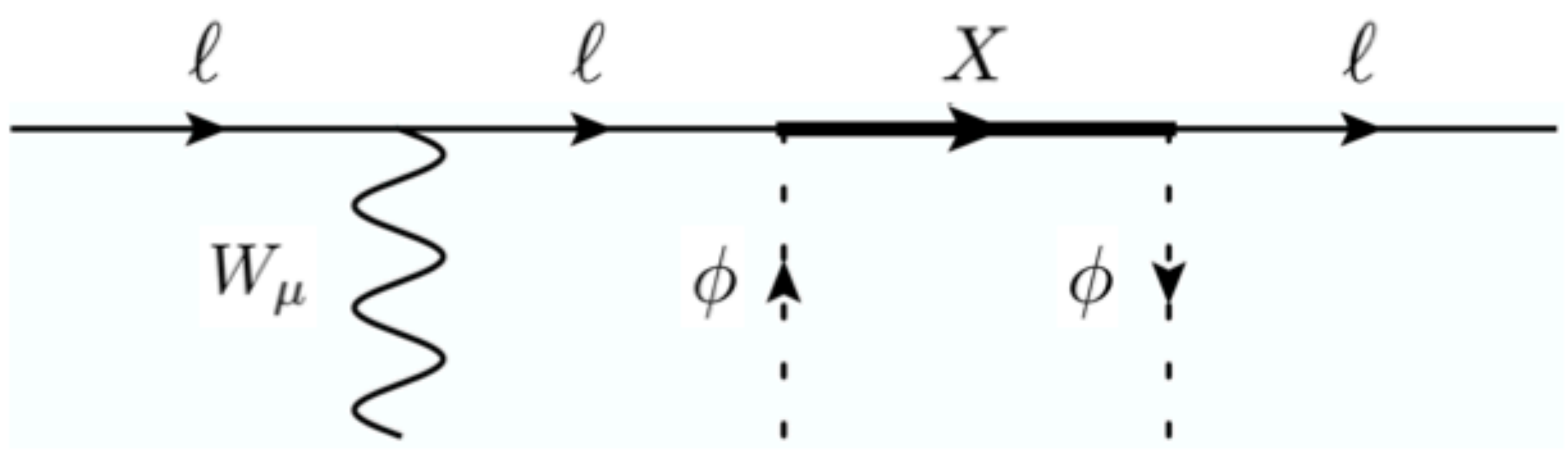
In what follows we neglect VLLs self interactions

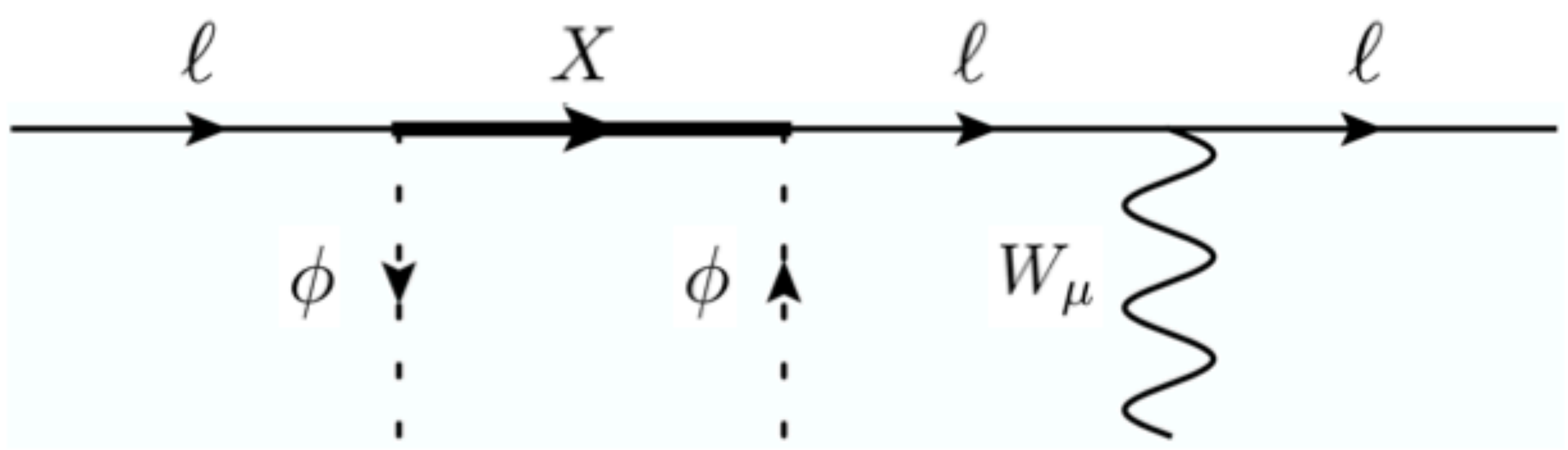
Vectorlike Leptons

- VLLs APPEAR IN SEVERAL EXTENSIONS OF THE SM: GUT, EXTRA DIMENSION, COMPOSITE MODELS, ETC.

- THEY MODIFY GAUGE BOSONS COUPLINGS TO LEPTONS ALREADY AT TREE-LEVEL AND THEREFORE IT IS IMPORTANT TO STUDY THE IMPACT ON TESTABLE OBSERVABLES







EFT Matching

- IT IS USEFUL TO DESCRIBE THE IMPACT OF VLLs IN TERMS OF EFFECTIVE OPERATORS

$$Q_{\phi\ell}^{(1)ij} = \phi^\dagger i \overleftrightarrow{D}_\mu \phi \bar{\ell}^i \gamma^\mu \ell^j \qquad Q_{\phi\ell}^{(3)ij} = \phi^\dagger i \overleftrightarrow{D}^I_\mu \phi \bar{\ell}^i \tau^I \gamma^\mu \ell^j \qquad Q_{\phi e}^{ij} = \phi^\dagger i \overleftrightarrow{D}_\mu \phi \bar{e}^i \gamma^\mu e^j$$

MATCHING

$$\frac{C_{\phi\ell}^{(1)}}{\Lambda^2} = \alpha \frac{|\lambda_X|^2}{M_X^2} \qquad \frac{C_{\phi\ell}^{(3)}}{\Lambda^2} = \beta \frac{|\lambda_X|^2}{M_X^2} \qquad \frac{C_{\phi e}}{\Lambda^2} = \gamma \frac{|\lambda_{\Delta_1}|^2}{M_{\Delta_1}^2}$$

	N	E	Δ_1	Δ_3	Σ_0	Σ_1
α	1/4	-1/4	-	-	3/16	-3/16
β	-1/4	-1/4	-	-	1/16	1/16
γ	-	-	1/2	-1/2	-	-

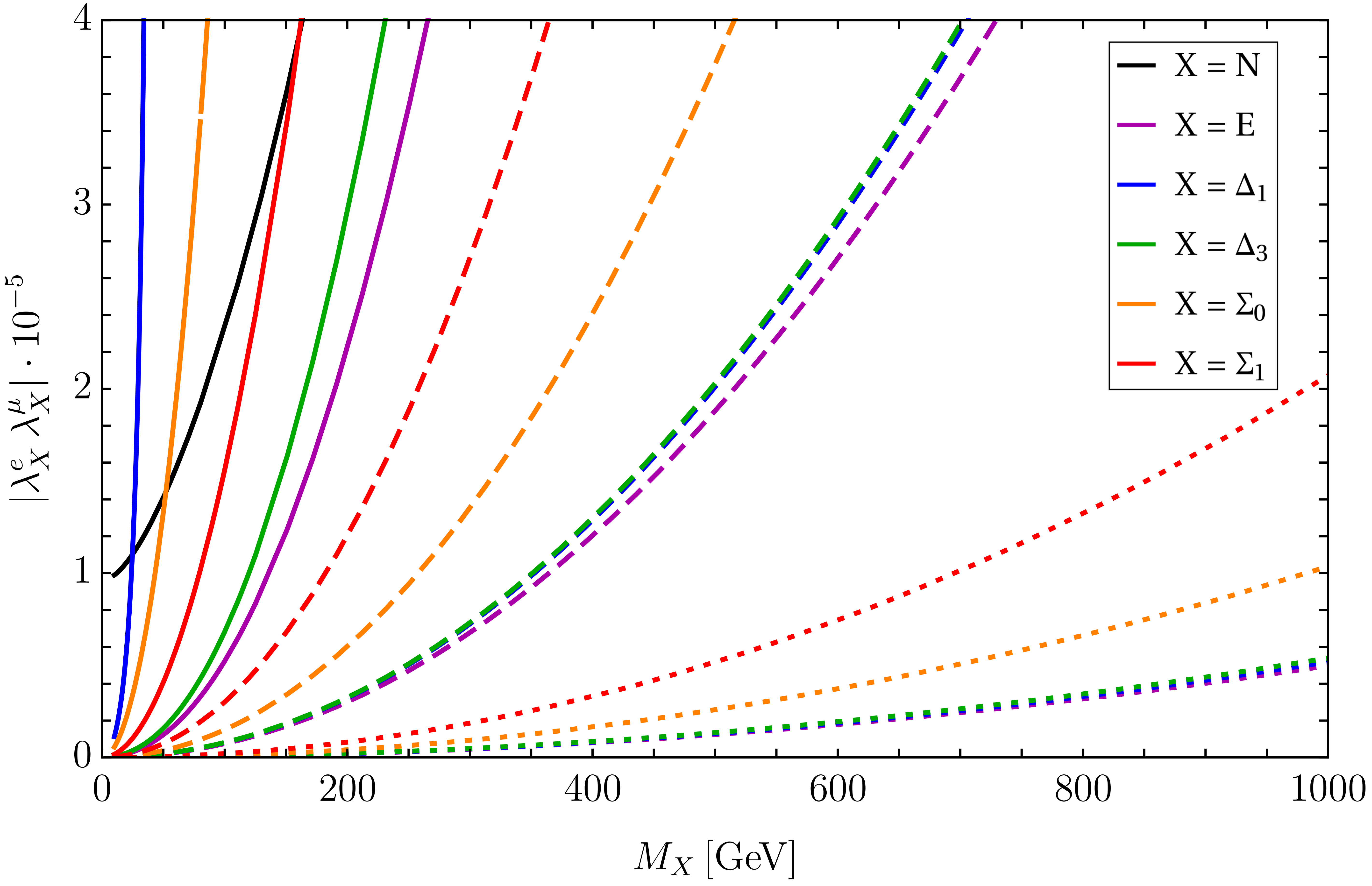
Flavour Violating Processes

These effects are inevitable if there is only one generation of VLLs coupling simultaneously to at least 2 generations of SM leptons

$\mu \to e\gamma$	solid line	1-LOOP
$\mu \to eee$	dashed line	TREE-LEVEL ($Z\ell\ell$)
$\mu \to e$ conv.	dotted line	TREE-LEVEL ($Z\ell\ell$)

↓

In the following we assume the presence of multiple VLL generations, each coupling to a different SM generation

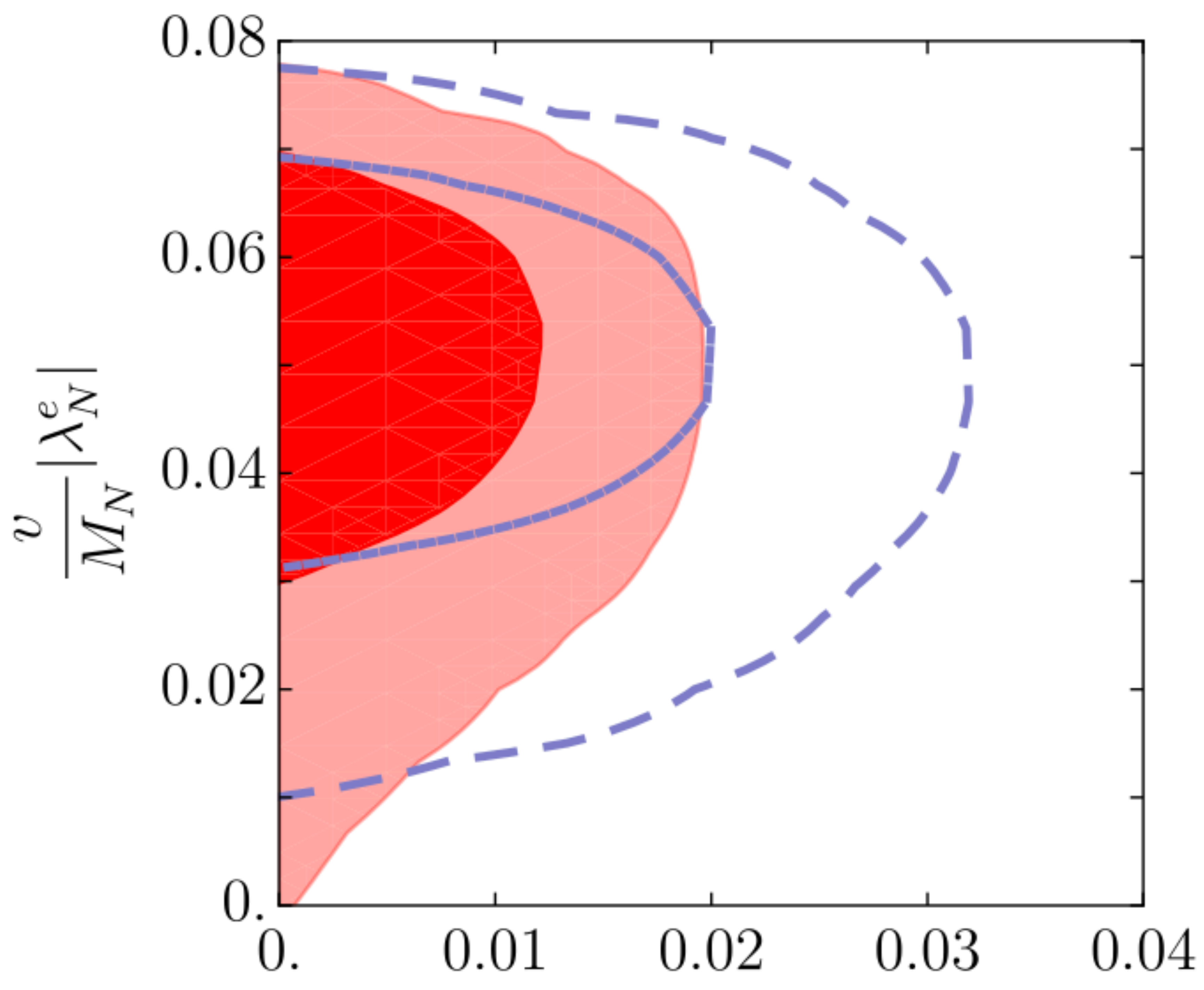


VLL Analysis

We performed a global fit to the pattern of couplings induced by each VLL generation

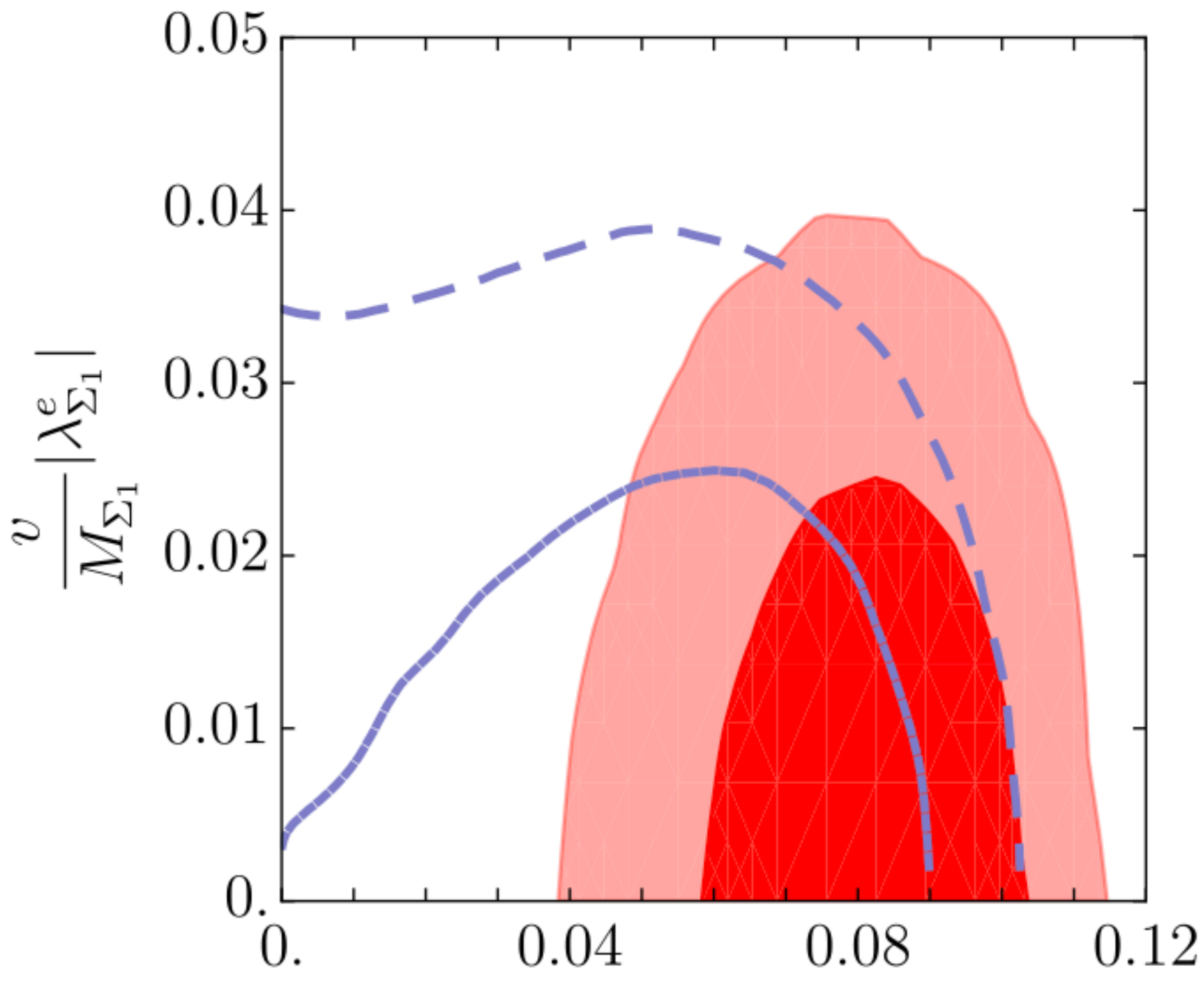
Each representation ALONE is not able to improve the agreement with data $IC_{SM} \simeq 93$

N:



$IC_N \simeq 93$ $\frac{v}{M_N}|\lambda_N^\mu|$

Σ_1:



$IC_{\Sigma_1} \simeq 92$ $\frac{v}{M_{\Sigma_1}}|\lambda_{\Sigma_1}^\mu|$

VLL Analysis

Allowing for two VLL at the same time...
we found a very interesting scenario,
strongly improving the agreement
with data:

N coupling with electrons

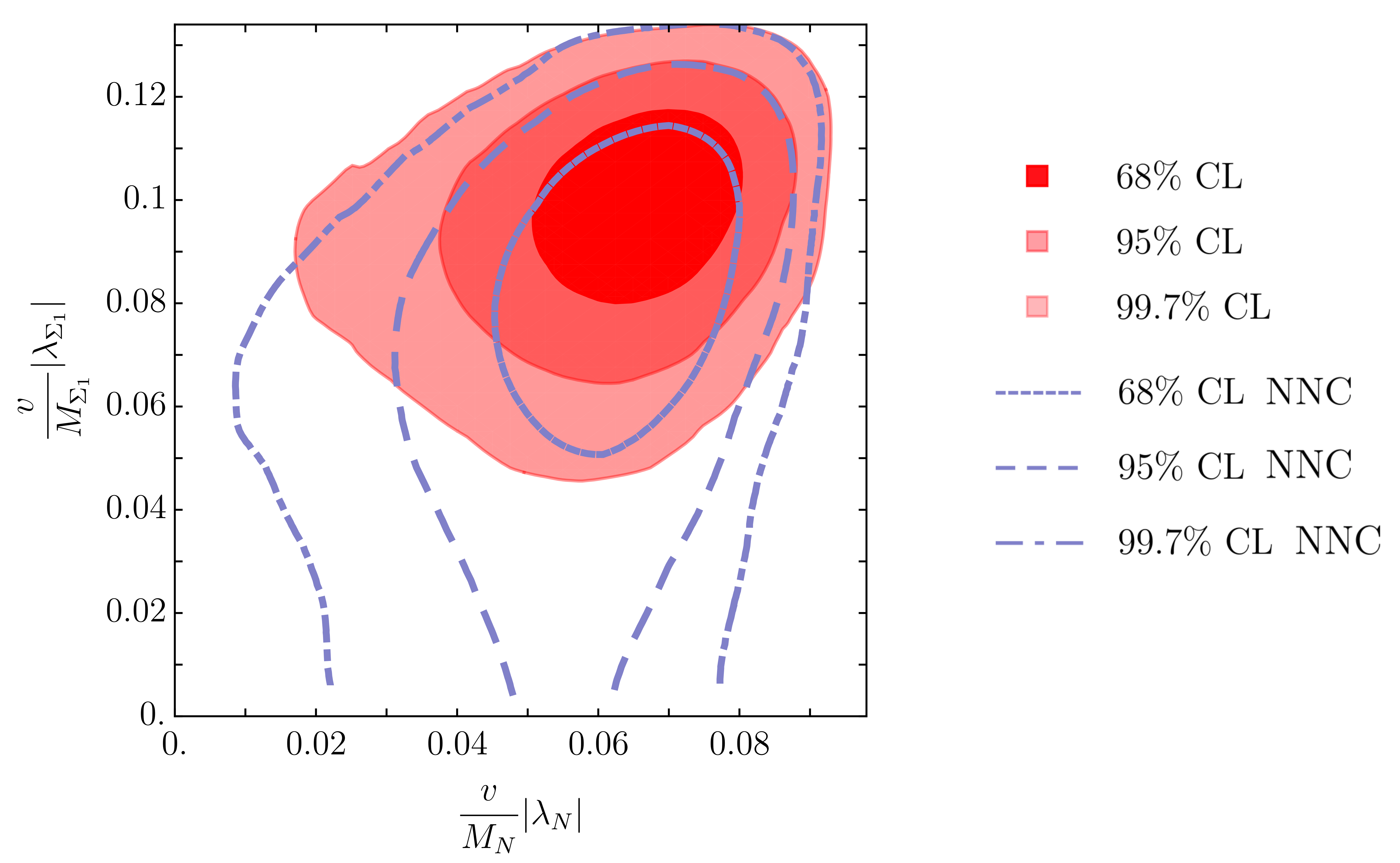
+

Σ_1 coupling with muons

$\mathrm{IC}_{\mathrm{SM}} \simeq 93$

$\mathrm{IC}_{\mathrm{NP}} \simeq 73$

BEST FIT REGIONS IN OUR MINIMAL SCENARIO



Conclusions

- VLLs are very interesting candidates to solve the Cabibbo-Angle anomaly and appear in several proposed extensions of the SM
- They naturally modify the gauge bosons couplings with SM leptons, therefore we took into account also data from EW precision measurements and observables testing LFU

Results

- Each representation describes data similarly to the SM;
- We found a minimal model consisting of 2 VLL representations which **solves the CAA** and **improves the agreement with data in the EW and LFU testing observables**.

N coupling with electrons + Σ_1 coupling with muons

Conclusions

IN OUR MINIMAL MODEL

Observable	Measurement	SM Posterior	NP Posterior	Pull
M_W [GeV]	80.379(12)	80.363(4)	80.369(6)	0.56
$R\left[\frac{K\to\mu\nu}{K\to e\nu}\right]$	0.9978 ± 0.0020	1	1.00168(39)	−0.80
$R\left[\frac{\pi\to\mu\nu}{\pi\to e\nu}\right]$	1.0010 ± 0.0009	1	1.00168(39)	0.42
$R\left[\frac{\tau\to\mu\nu\bar{\nu}}{\tau\to e\nu\bar{\nu}}\right]$	1.0018 ± 0.0014	1	1.00168(39)	1.2
$\lvert V_{us}^{K_{\mu 3}}\rvert$	0.22345(67)	0.22573(35)	0.22519(39)	0.77
$\lvert V_{ud}^{\beta}\rvert$	0.97365(15)	0.97419(8)	0.97378(13)	2.52

Observables showing the best and worst pull comparing our minimal model with the SM

$$|V_{us}|^2 + |V_{ud}|^2 (1-\varepsilon)^2 + |V_{ub}|^2 = 0.9985(5)$$

$$\varepsilon = \frac{v^2}{16}\frac{\lambda_{\Sigma_1}^2}{M_{\Sigma_1}^2} \simeq 0.00063$$

$$|V_{us}|^2 + |V_{ud}|^2 + |V_{ub}|^2 = 0.9998(5)$$