Vector-Like Leptons
in Light of the Cabibbo Angle Anomaly

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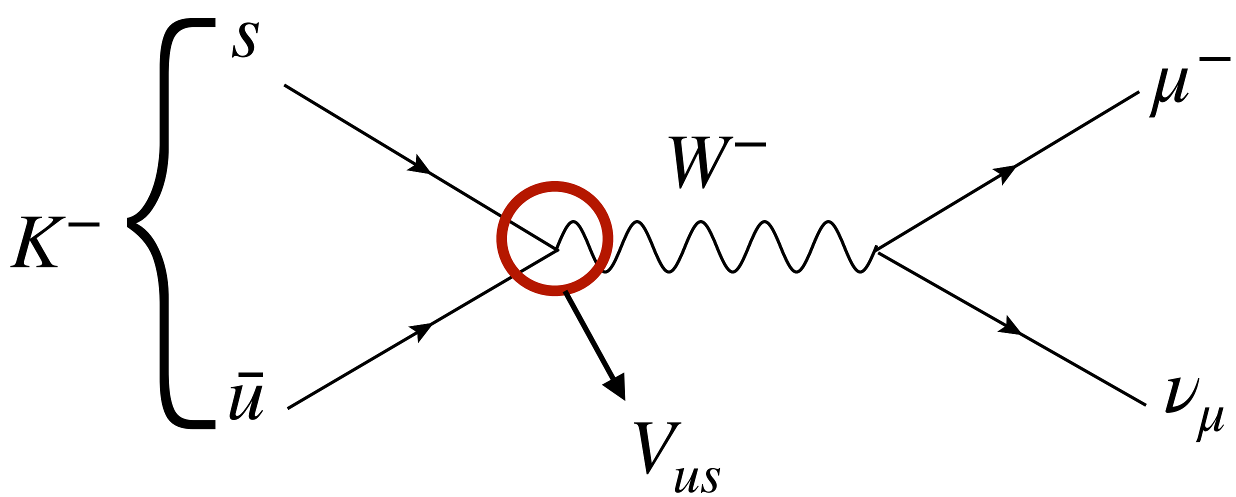
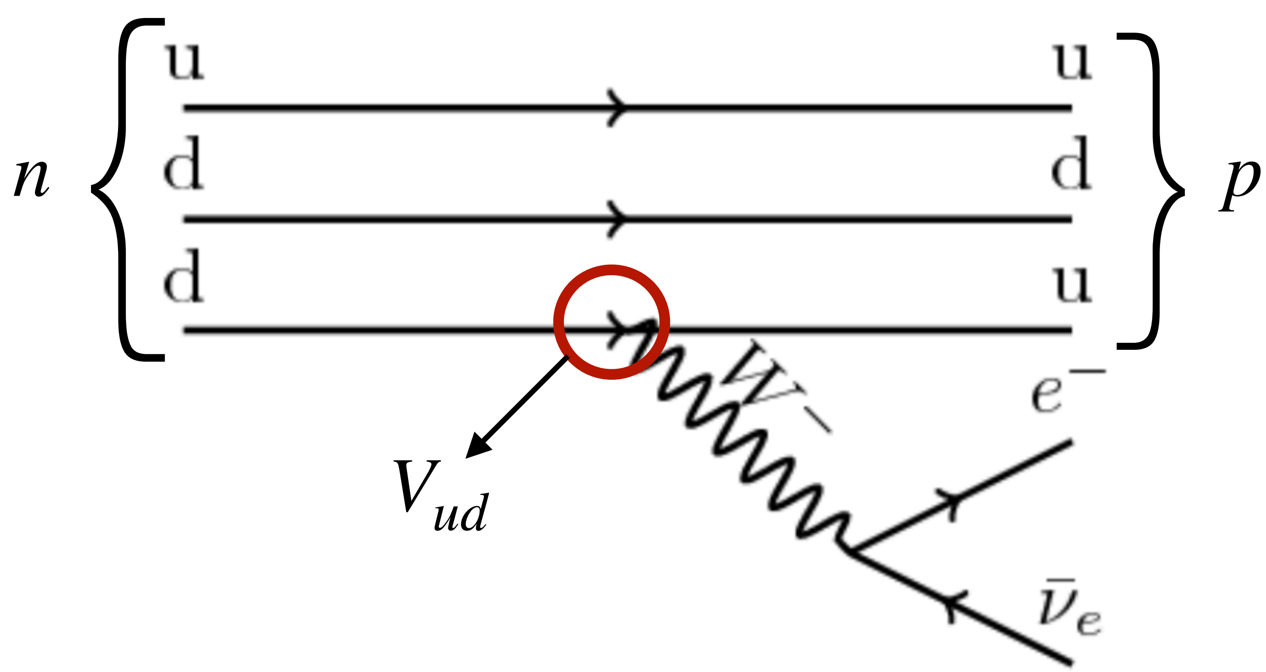
The CKM matrix

The unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix parametrises the misalignment between interaction and mass bases in the quark sector.

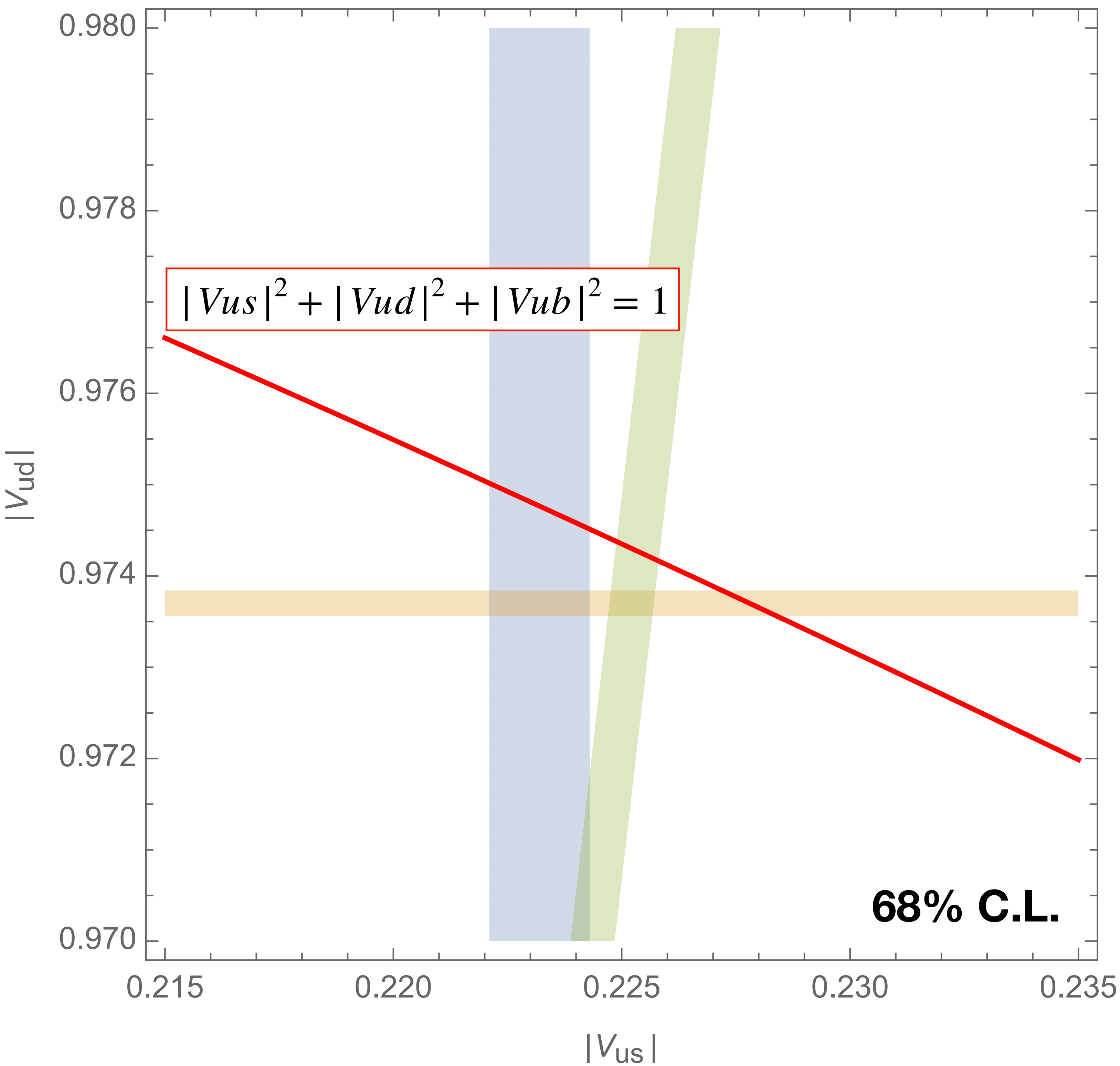


$$|Vud|^2 + |Vus|^2 + |Vub|^2 = 1$$

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$



The Anomaly



- $K \to \pi \ell \nu\ +\ f_+(0)$:

  $$|V_{us}| = 0.2232(11)$$

- $\frac{K \to \mu\nu}{\pi \to \mu\nu} + \frac{f_{K^\pm}}{f_{\pi^\pm}}$

  $$\left|\frac{V_{us}}{V_{ud}}\right| = 0.2313(5)$$

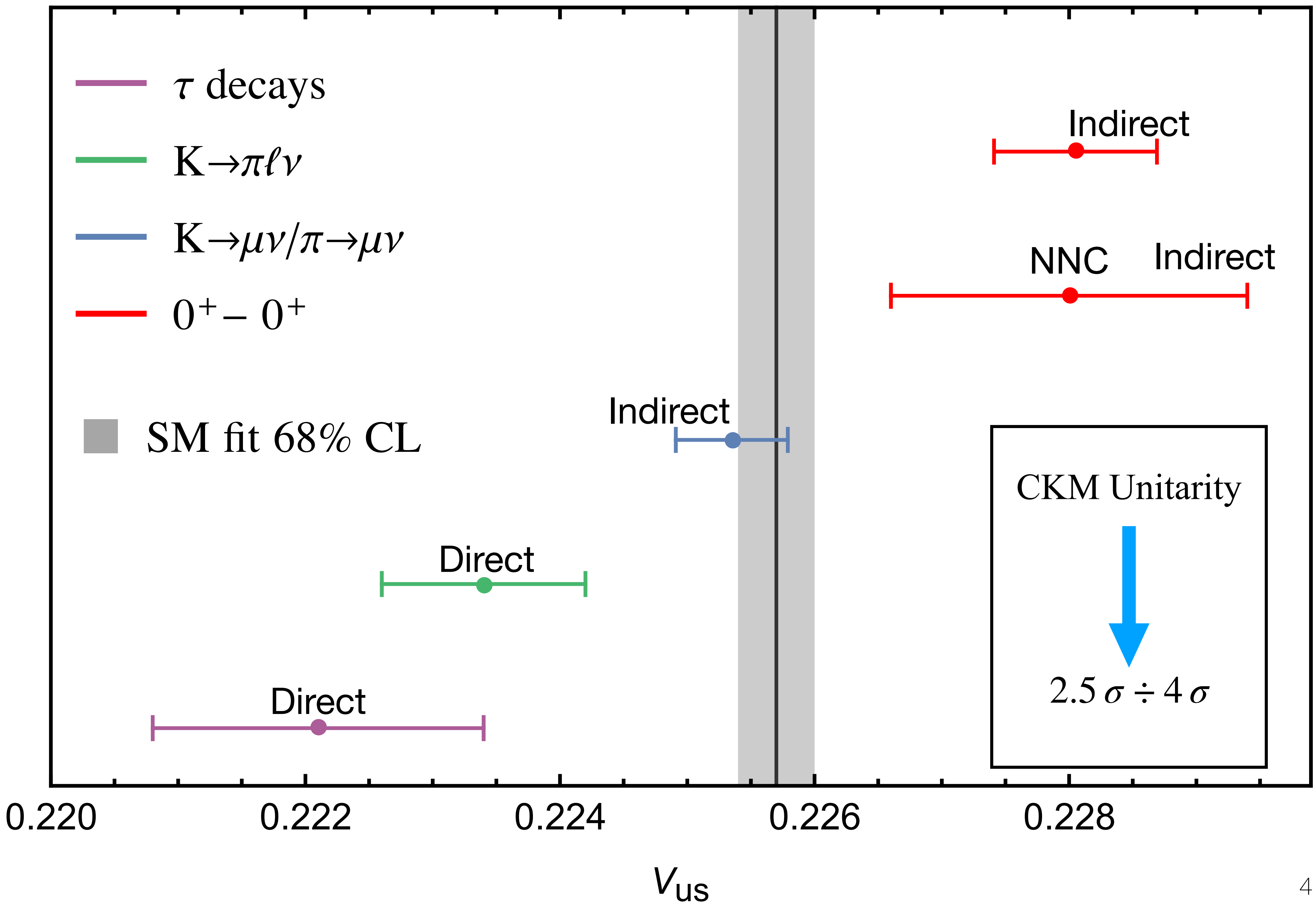
- $0^+ - 0^+\ +$ corrections

  $$|V_{ud}| = 0.97365(15)$$

  $$|V_{ud}|_{\text{NNC}} = 0.97366(33)$$

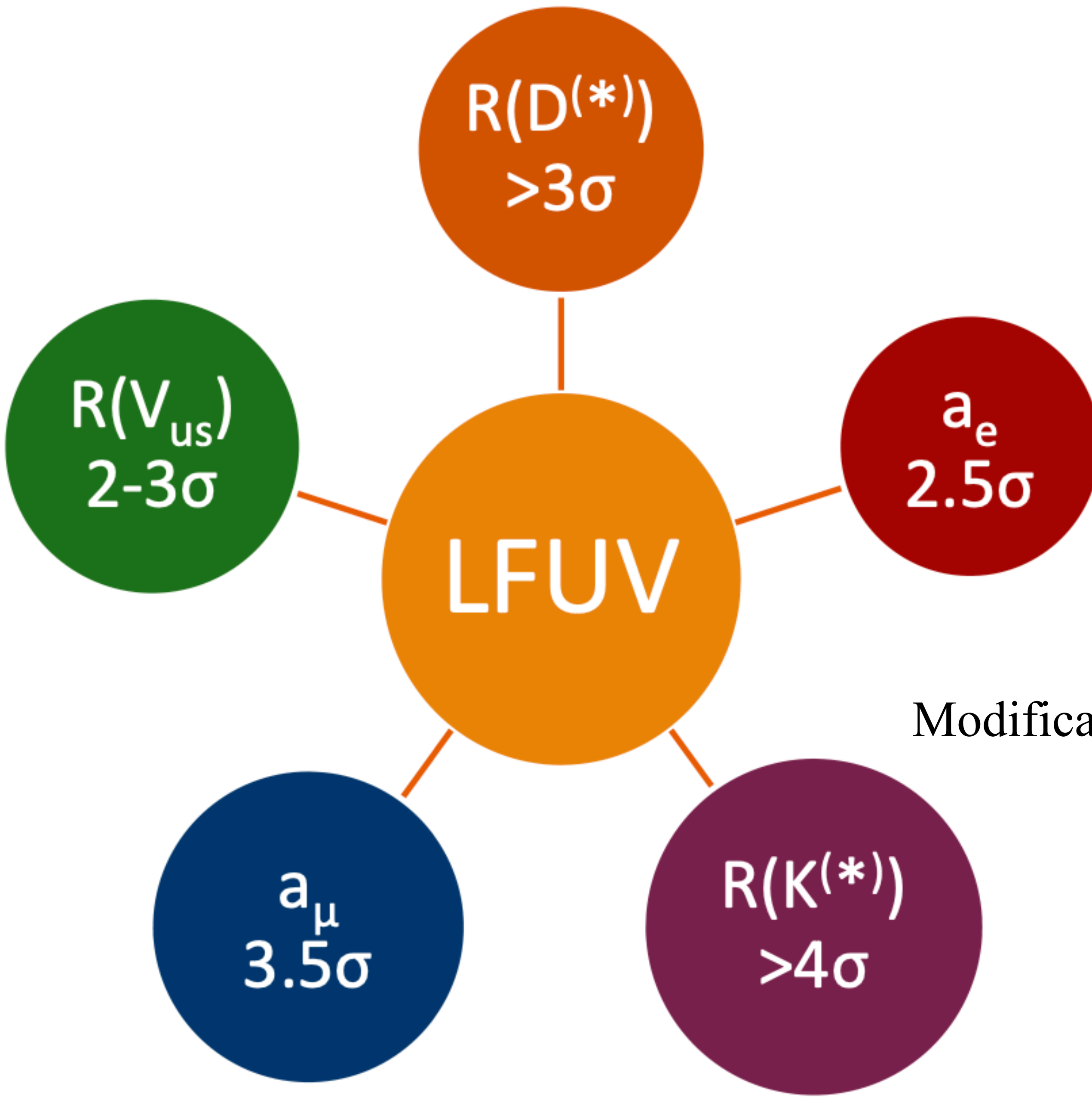
The Anomaly

There is a tension between the different determinations of V_{us}



LFUV

$R(V_{us}) = \dfrac{V_{us}^{K/\pi}}{V_{us}^{\beta}}$ as a test of LFUV complements to an already interesting picture



$$R(V_{us})\Big|_{\text{SM}} = 1$$

$$R(V_{us}) \simeq 1 - \underbrace{\left(\frac{V_{ud}^{\mathscr{L}}}{V_{us}^{\mathscr{L}}}\right)^2}_{\sim 20} \frac{\epsilon_{\mu\mu}}{2}$$

Modification of the coupling of the W with muons

EFT Setup

Minimal Approach

Consider operators which modify only the couplings of W and Z to leptons

dim = 6

$$\mathscr{L} = \mathscr{L}_{\rm SM} + \frac{1}{\Lambda^2}\left(C^{(1)}_{\phi\ell} Q^{(1)}_{\phi\ell} + C^{(3)}_{\phi\ell} Q^{(3)}_{\phi\ell} + C_{\phi e} Q_{\phi e} \right)$$

$$Q^{(1)}_{\phi\ell} = \phi^\dagger i \overleftrightarrow{D}_\mu \phi \bar{\ell}_L \gamma^\mu \ell_L \qquad Q^{(3)}_{\phi\ell} = \phi^\dagger i \overleftrightarrow{D}^I_\mu \phi \bar{\ell}_L \tau^I \gamma^\mu \ell_L \qquad Q_{\phi e} = \phi^\dagger i \overleftrightarrow{D}_\mu \phi \bar{e}_R \gamma^\mu e_R$$

Modifications of the Gauge Bosons Couplings

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

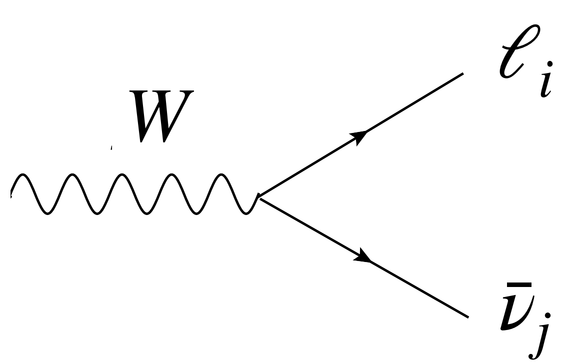
$$Z \to \nu\nu \propto C^{(3)}_{\phi\ell} - C^{(1)}_{\phi\ell} \qquad W \to \ell\nu \propto C^{(3)}_{\phi\ell}$$

Modified Neutrino Couplings

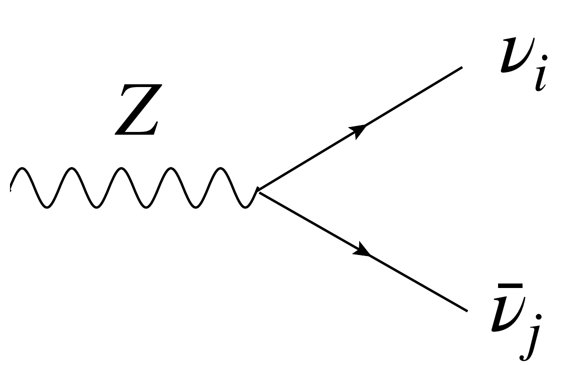
Minimal impact: **we modify only the couplings of W and Z with neutrinos**

- EW observables
- Low energy observables (K, π, τ, W decays)

$$\frac{v^2}{\Lambda^2} C^{(3)}_{\phi\ell} = -\frac{v^2}{\Lambda^2} C^{(1)}_{\phi\ell} = \varepsilon \quad \text{and} \quad C_{\phi e} = 0\,;$$



$$\frac{-ig_2}{\sqrt{2}} \Rightarrow \frac{-ig_2}{\sqrt{2}} \left(\delta_{ij} + \frac{1}{2} \varepsilon_{ij} \right)$$



$$\frac{-ig_2}{2c_W} \Rightarrow \frac{-ig_2}{2c_W} \left(\delta_{ij} + \varepsilon_{ij} \right)$$

LFV Parameters

Non-diagonal elements of ϵ_{ij} lead to charged lepton flavour violation

$$\mathrm{Br}[\mu \to e\gamma] \to |\epsilon_{e\mu}| \lesssim 10^{-5}$$

$$\mathrm{Br}[\tau \to \mu\gamma] \to |\epsilon_{\tau\mu}| \lesssim 10^{-2}$$

$$\mathrm{Br}[\tau \to e\gamma] \to |\epsilon_{\tau e}| \lesssim 10^{-2}$$

In flavour conserving processes do not interfere with the SM contributions, and enter only quadratically, therefore they are further suppressed.

Assume in the following diagonal ε_{ij}

Parameters and Observables

NP Parameters :

$$\epsilon_{ee}, \quad \epsilon_{\mu\mu}, \quad \epsilon_{\tau\tau}$$

EW Parameters

$$G_F, \quad \alpha, \quad M_Z$$

$$G_F^{\exp} = G_F^{\mathcal{L}}\left(1 + \frac{1}{2}\varepsilon_{ee} + \frac{1}{2}\varepsilon_{\mu\mu}\right)$$

V_{us}

$$|V_{us}^{K_{\mu 3}}| \approx |V_{us}^{\mathcal{L}}|\left(1 - \frac{1}{2}\varepsilon_{ee}\right)$$

$$|V_{us}^{\beta}| \approx \sqrt{1 - |V_{ud}^{\mathcal{L}}|^2\left(1 - \frac{1}{2}\varepsilon_{\mu\mu}\right)^2}$$

Not affected

$$|V_{us}^{K/\pi}|$$

$$|V_{us}^{\tau\to K/\pi}|$$

$$|V_{us}^{\tau\to X\nu}|$$

Parameters and Observables

Test of LFU in the charged current

These measurements together with the EW precision tests constraint the size of our parameters

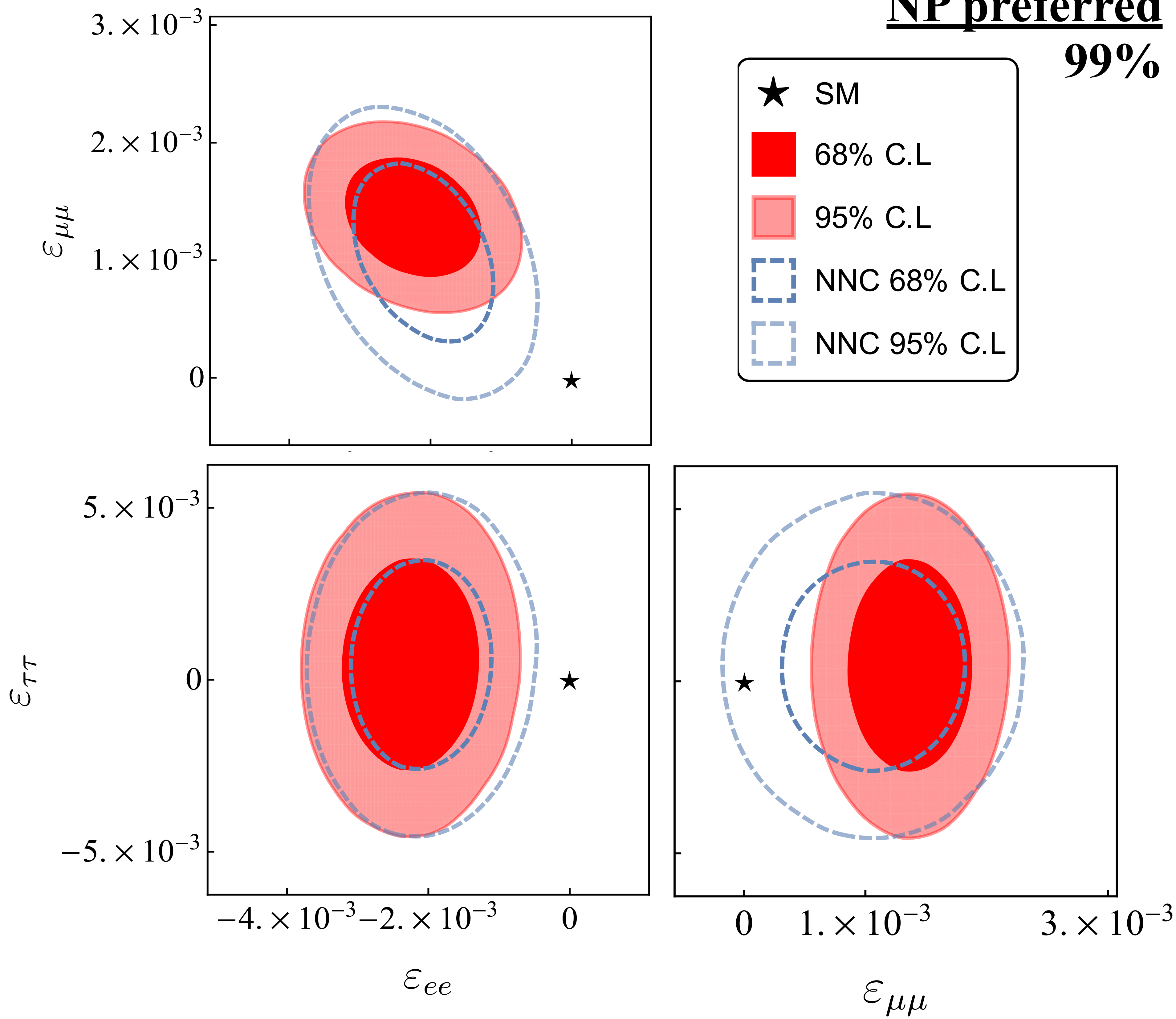
$$\frac{\pi\to\mu\nu}{\pi\to e\nu}\sim\left.\frac{\pi\to\mu\nu}{\pi\to e\nu}\right|_{\rm SM}\left(1+\frac{1}{2}\epsilon_{\mu\mu}-\frac{1}{2}\epsilon_{ee}\right)\qquad\left\{\begin{matrix}\dfrac{K\to\mu\nu}{K\to e\nu} & \dfrac{\tau\to\mu\nu\nu}{\tau\to e\nu\nu}\\ \dfrac{K\to\pi\mu\nu}{K\to\pi e\nu} & \dfrac{W\to\mu\nu}{W\to e\nu}\end{matrix}\right.$$

$$\frac{\tau\to e\nu\nu}{\mu\to e\nu\nu}\sim\left.\frac{\tau\to e\nu\nu}{\mu\to e\nu\nu}\right|_{\rm SM}\left(1+\frac{1}{2}\epsilon_{\tau\tau}-\frac{1}{2}\epsilon_{\mu\mu}\right)\qquad\left\{\begin{matrix}\dfrac{\tau\to\pi\nu}{\pi\to\mu\nu} & \dfrac{\tau\to K\nu}{K\to\mu\nu}\\ \multicolumn{2}{c}{\dfrac{W\to\tau\nu}{W\to\mu\nu}}\end{matrix}\right.$$

$$\frac{\tau\to\mu\nu\nu}{\mu\to e\nu\nu}\sim\left.\frac{\tau\to\mu\nu\nu}{\mu\to e\nu\nu}\right|_{\rm SM}\left(1+\frac{1}{2}\epsilon_{\tau\tau}-\frac{1}{2}\epsilon_{ee}\right)\qquad\left\{\dfrac{W\to\tau\nu}{W\to e\nu}\right.$$

<u>A **global fit** to all the data is necessary!</u>

Global Fit



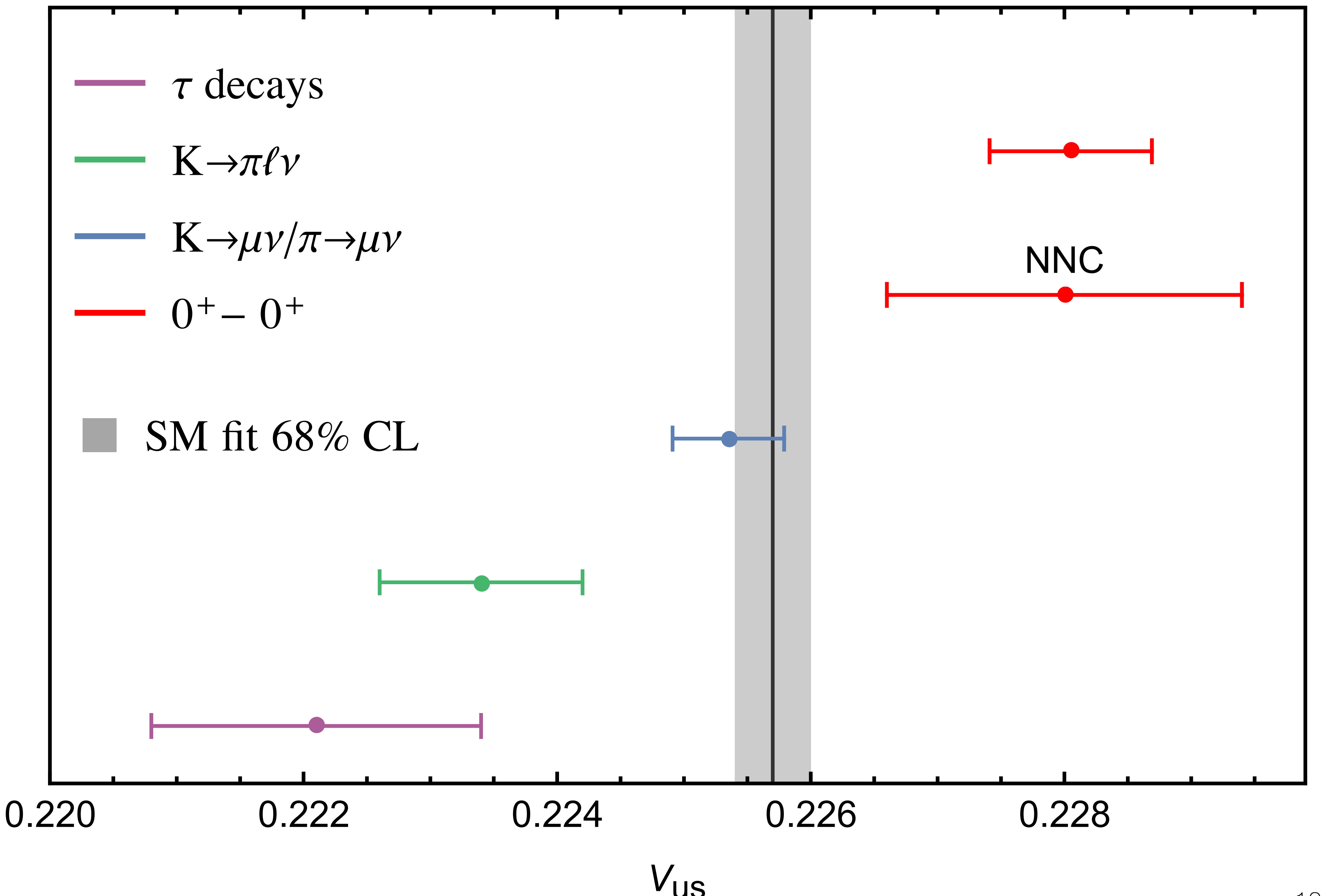
NP preferred at more than 99% C.L.

$\mathrm{IC_{SM}} \simeq 93$

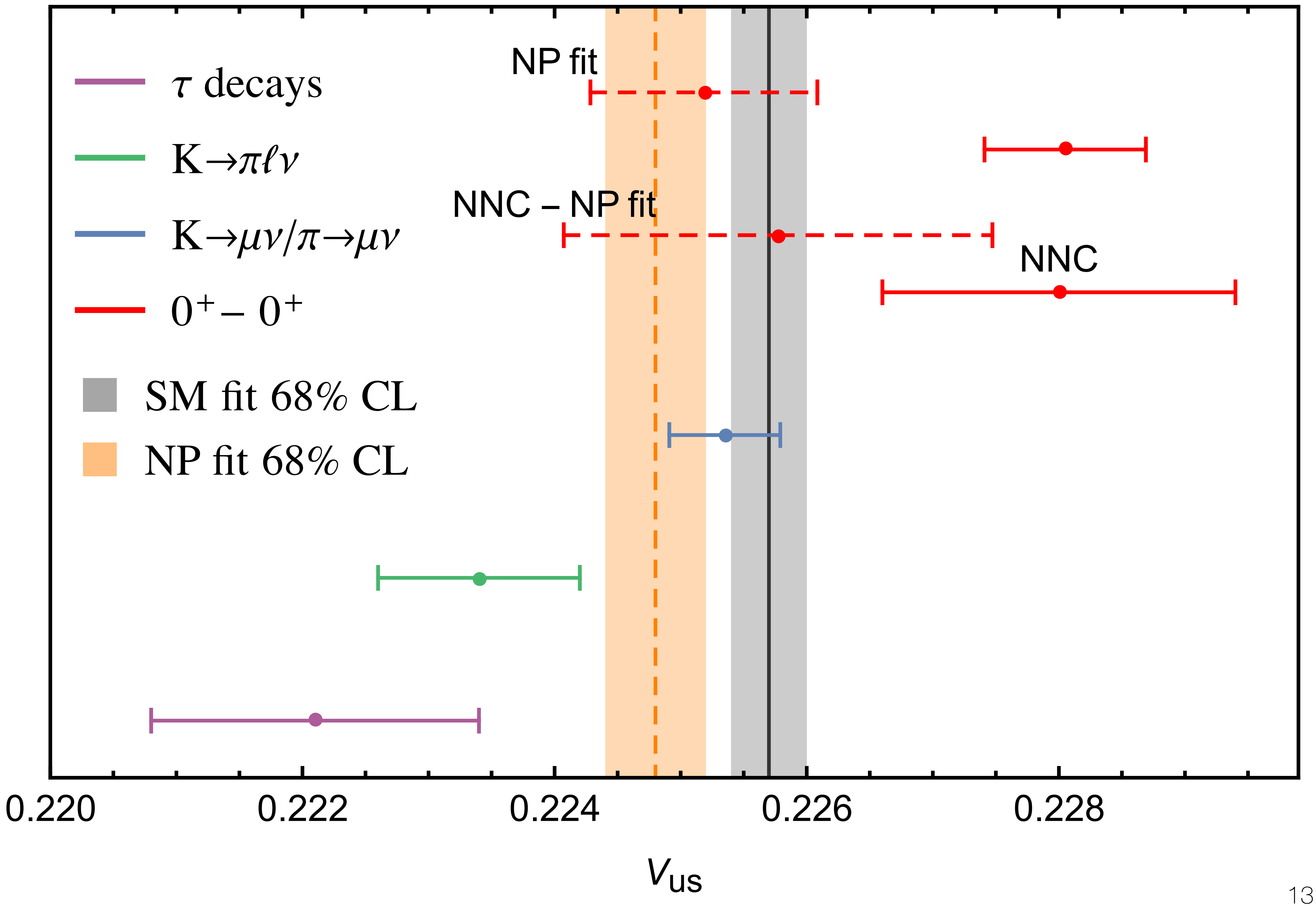
$\mathrm{IC_{NP}} \simeq 76$

HEPfit

Anomaly in the SM



Anomaly in the NP Scenario



Vector-Like Leptons

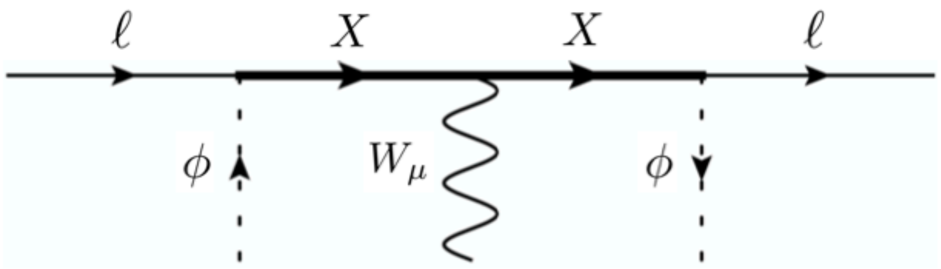
VLLs are fermions whose left and right-handed components have the same representations of $SU(2)_L \times U(1)_Y$, are singlets under QCD and can couple to the SM Higgs and SM leptons via Yukawa-like couplings.

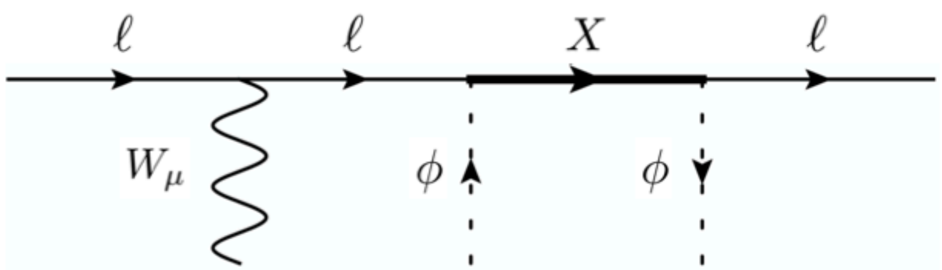
Prime Candidates since they modify $W \to \ell\nu$ **at tree-level**

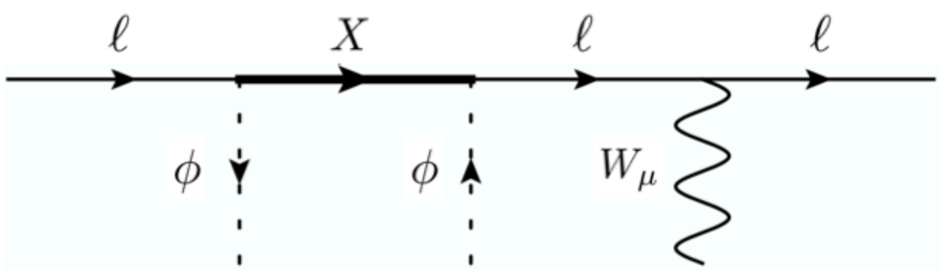
	$SU(3)$	$SU(2)_L$	$U(1)_Y$
ℓ	1	2	-1/2
e	1	1	-1
ϕ	1	2	1/2
N	1	1	0
E	1	1	-1
$\Delta_1 = (\Delta_1^0, \Delta_1^-)$	1	2	-1/2
$\Delta_3 = (\Delta_3^-, \Delta_3^{--})$	1	2	-3/2
$\Sigma_0 = (\Sigma_0^+, \Sigma_0^0, \Sigma_0^-)$	1	3	0
$\Sigma_1 = (\Sigma_1^0, \Sigma_1^-, \Sigma_1^{--})$	1	3	-1

Vector-Like Leptons

Prime Candidates since they modify $W \to \ell\nu$ **at tree-level**







$$\frac{C_{\phi\ell}^{(1)}}{\Lambda^2} = \alpha \frac{|\lambda_X|^2}{M_X^2}$$

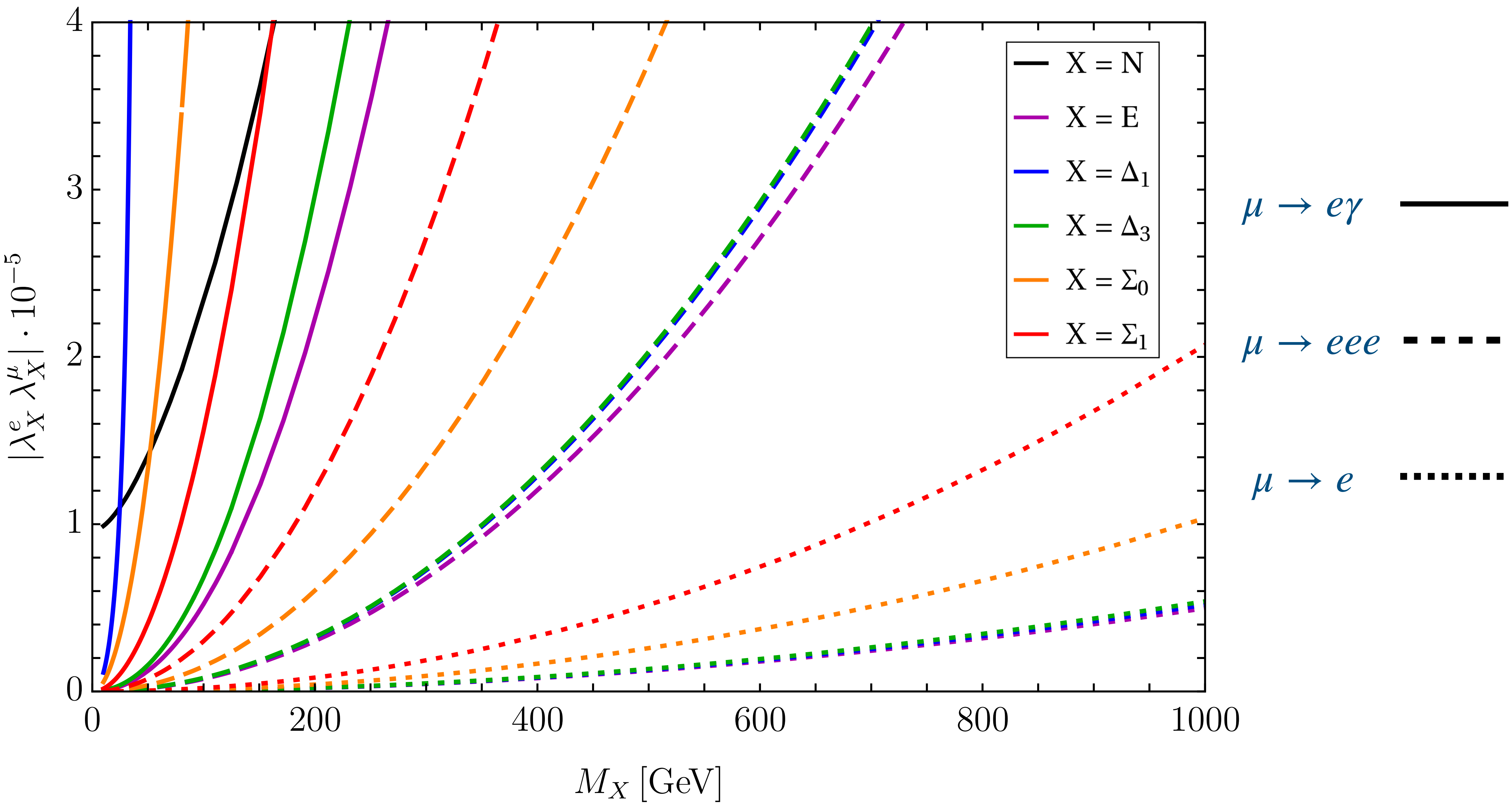
$$\frac{C_{\phi\ell}^{(3)}}{\Lambda^2} = \beta \frac{|\lambda_X|^2}{M_X^2}$$

$$\frac{C_{\phi e}}{\Lambda^2} = \gamma \frac{|\lambda_{\Delta_1}|^2}{M_{\Delta_1}^2}$$

	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

VLL can contribute to $\ell \to \ell'\gamma$, $\ell \to 3\ell$ and $\mu \to e$ conversion



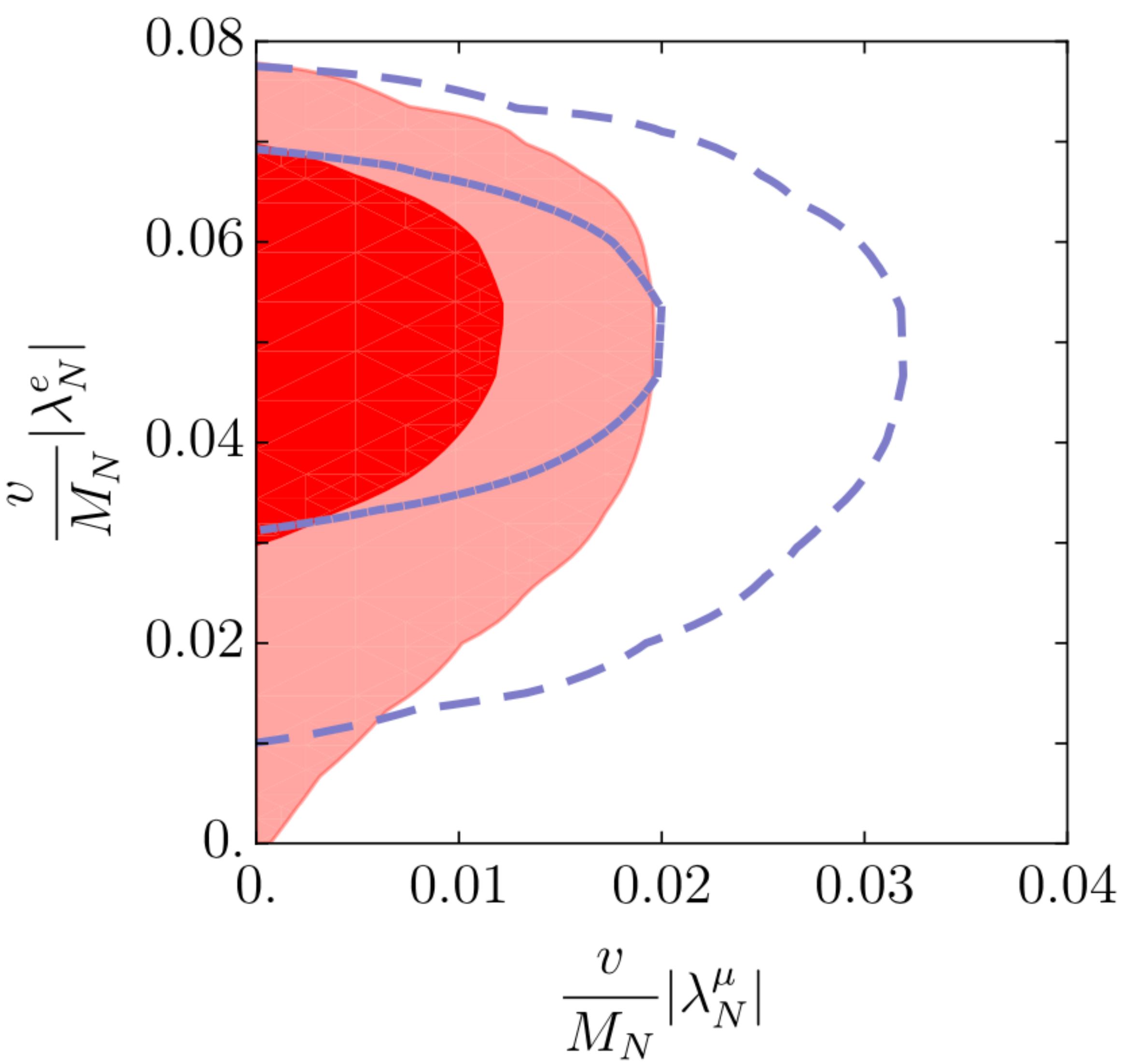
Note that this bounds can **always** be avoided requiring multiple VLL generations

Global Fit to VLL

- Each representation alone describes data similarly to the SM. $IC_{SM} \simeq 93$

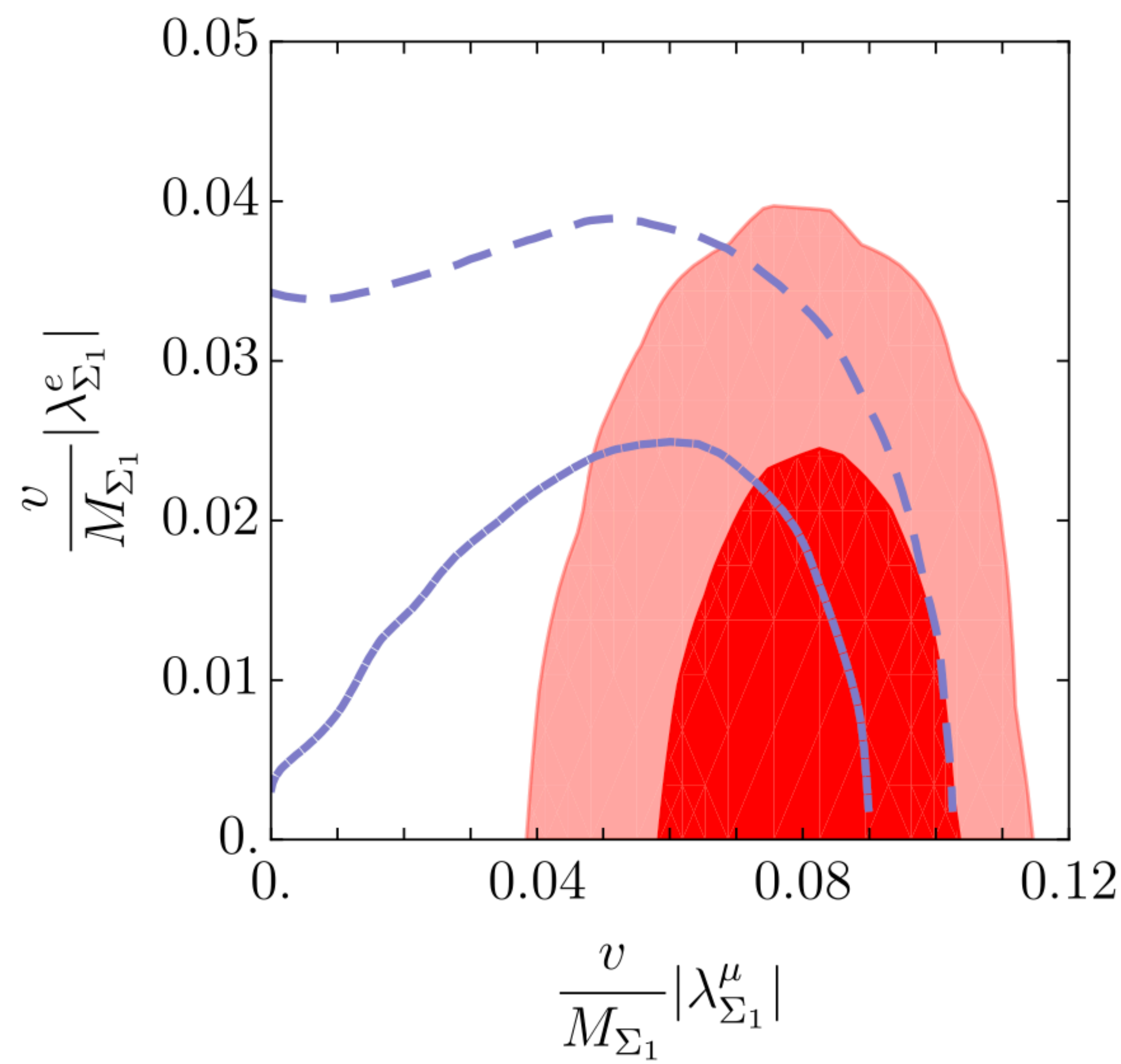
Ex.: N

$IC_N \simeq 93$



Ex.: Σ_1

$IC_{\Sigma_1} \simeq 92$



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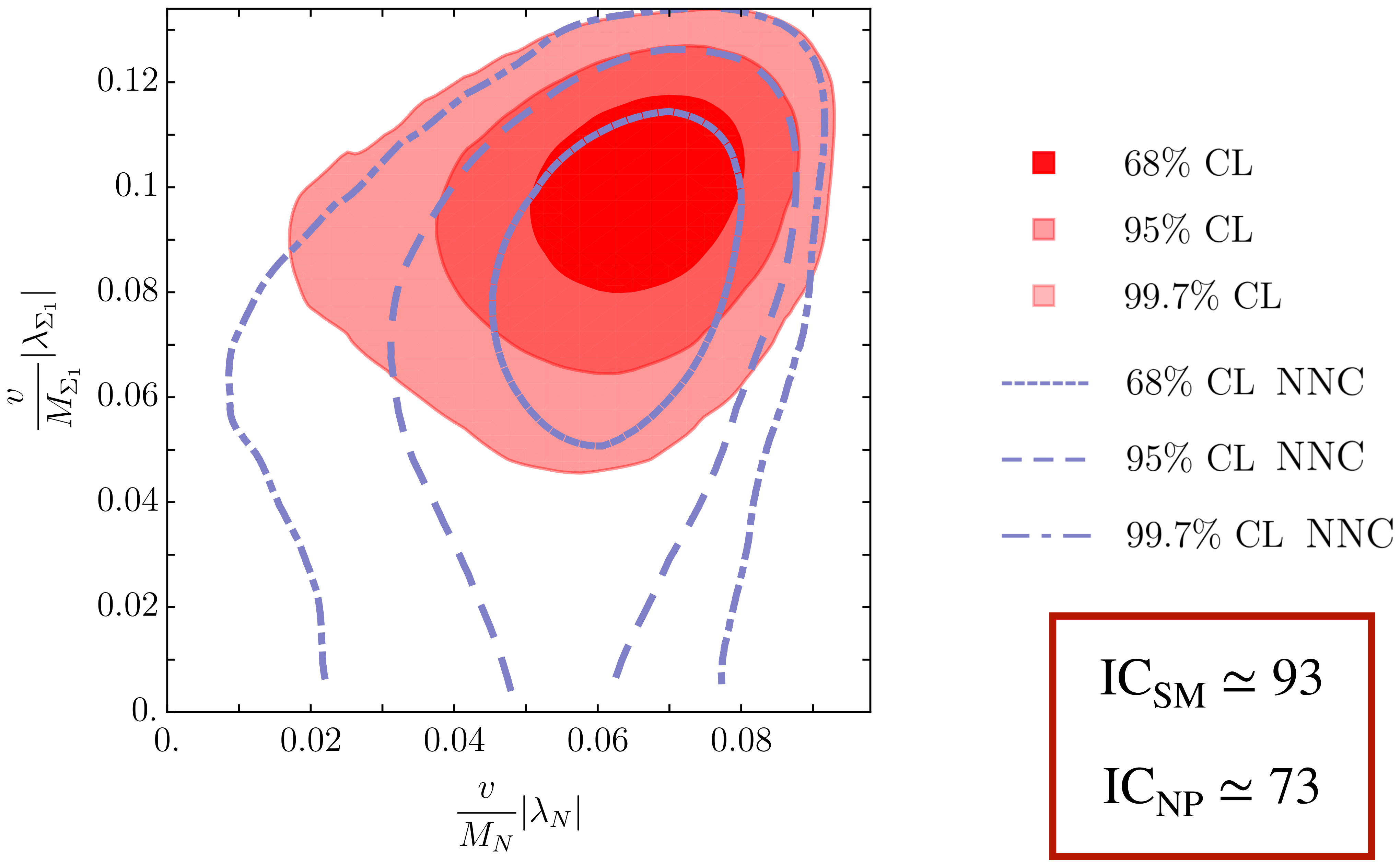
VLL Minimal Model

- We found a minimal scenario strongly improving the agreement with data:

N coupling with electrons and Σ_1 coupling with muons



$IC_{SM} \simeq 93$

$IC_{NP} \simeq 73$

Conclusions (I)

- There is a tension in the determination of V_{us} from different processes

- It can be interpreted as an evidence of LFUV completing an already interesting picture

- The CAA points towards $W\ell\nu$ modified couplings. Therefore we performed a global fit to all the observables affected by those modifications.

- The global fit to EW, LFU and V_{us} prefers LFUV NP at more than 99% C.L.

Conclusions (II)

- VLLs are very interesting candidates to solve this anomaly.
- For each representation we extracted the bounds from EW, LFU and V_{us} obs.
- We found a minimal model strongly improving the agreement with data:

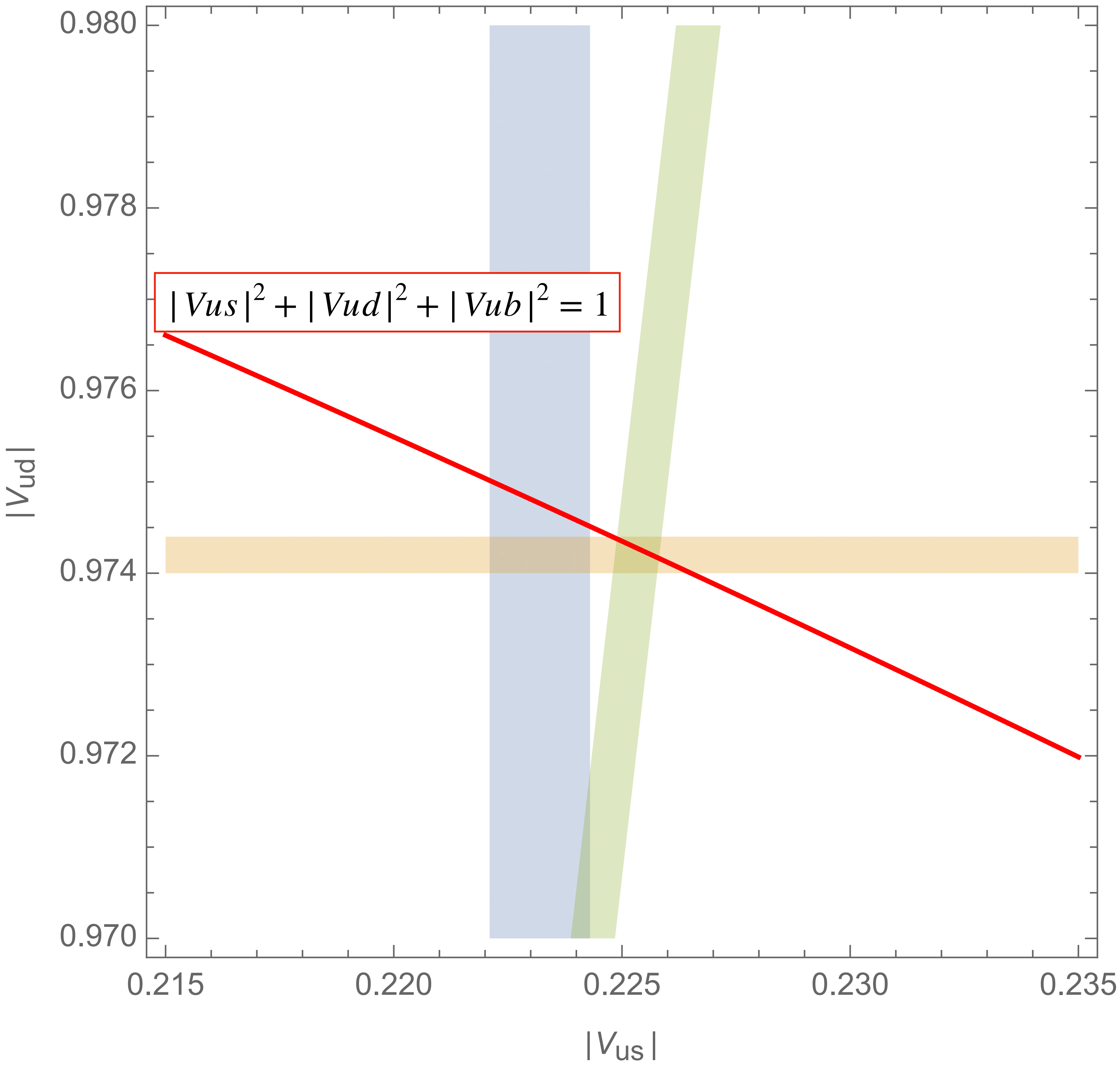
N coupling with electrons and Σ_1 coupling with muons

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
$\lvert V_{us}^{K_{\mu3}}\rvert$	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

Best and worst pulls of our minimal model with respect to the SM

Backup

The Anomaly with NP



- $K \to \pi \ell \nu \, + \, f_+(0)$:

$$|V_{us}| = 0.2232(11)$$

- $\dfrac{K \to \mu\nu}{\pi \to \mu\nu} + \dfrac{f_{K^\pm}}{f_{\pi^\pm}}$

$$\left|\frac{V_{us}}{V_{ud}}\right| = 0.2313(5)$$

- $0^+ - 0^+$ + corrections

$$|V_{ud}| = 0.97365(15)$$

$$|V_{ud}|_{\text{NNC}} = 0.97366(33)$$

Parameters of the Fit

Parameters of the Model Independent global fit

Parameter	Prior	SM posterior
G_F [GeV^{-2}] [3]	$1.1663787(6) \times 10^{-5}$	$\star$
α [3]	$7.2973525664(17) \times 10^{-3}$	$\star$
$\Delta\alpha_{\text{had}}$ [3]	$276.1(11) \times 10^{-4}$	$275.4(10) \times 10^{-4}$
$\alpha_s(M_Z)$ [3]	$0.1181(11)$	$\star$
m_Z [GeV] [7]	91.1875 ± 0.0021	91.1883 ± 0.0020
m_H [GeV] [9, 10]	125.16 ± 0.13	$\star$
m_t [GeV] [11–13]	172.80 ± 0.40	172.96 ± 0.39

	Prior	NP-II posterior
$V_{us}^{\mathcal{L}}$	0.225 ± 0.010	0.2248 ± 0.0004
ε_{ee}	0.00 ± 0.05	-0.0022 ± 0.0007
$\varepsilon_{\mu\mu}$	0.00 ± 0.05	0.0012 ± 0.0003
$\varepsilon_{\tau\tau}$	0.00 ± 0.05	-0.0003 ± 0.0020

NP – II ≡ NP scenario without NNC

EW Observables

Observables included in the Model Independent global fit

Observable	Ref.	Measurement	SM Posterior	NP-II posterior	Pull II
M_W [GeV]	[3]	80.379(12)	80.363(4)	80.370(6)	0.59
Γ_W [GeV]	[3]	2.085(42)	2.089(1)	2.090(1)	-0.02
BR($W \to$ had)	[3]	0.6741(27)	0.6749(1)	0.6749(1)	0
$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{\text{FB}}^{\text{had}})$	[3]	0.2324(12)	0.2316(4)	0.2315(1)	-0.1
$\sin^2\theta_{\text{eff(Tev)}}^{\text{lept}}$	[3]	0.23148(33)	0.2316(4)	0.2315(1)	0.17
$\sin^2\theta_{\text{eff(LHC)}}^{\text{lept}}$	[3]	0.23104(49)	0.2316(4)	0.2315(1)	-0.03
P_τ^{pol}	[7]	0.1465(33)	0.1461(3)	0.1472(8)	-0.09
A_ℓ	[7]	0.1513(21)	0.1461(3)	0.1472(8)	0.60
Γ_Z [GeV]	[7]	2.4952(23)	2.4947(6)	2.496(1)	-0.11
σ_h^0 [nb]	[7]	41.541(37)	41.485(6)	41.493(24)	0.42
R_ℓ^0	[7]	20.767(35)	20.747(7)	20.749(7)	0.06
$A_{\text{FB}}^{0,\ell}$	[7]	0.0171(10)	0.0160(7)	0.0163(2)	0.12
R_b^0	[7]	0.21629(66)	0.21582(1)	0.21582(1)	0
R_c^0	[7]	0.1721(30)	0.17219(2)	0.17220(2)	0
$A_{\text{FB}}^{0,b}$	[7]	0.0992(16)	0.1024(2)	0.1032(6)	-0.36
$A_{\text{FB}}^{0,c}$	[7]	0.0707(35)	0.0731(2)	0.0738(4)	-0.20
A_b	[7]	0.923(20)	0.93456(2)	0.9347(1)	-0.01
A_c	[7]	0.670(27)	0.6675(1)	0.6680(3)	0

$$P(O_i) = \left|\frac{O_i^{\text{exp}} - O_i^{\text{SM}}}{\sqrt{(\sigma_i^{\text{exp}})^2 + (\sigma_i^{\text{SM}})^2}}\right| - \left|\frac{O_i^{\text{exp}} - O_i^{\text{NP}}}{\sqrt{(\sigma_i^{\text{exp}})^2 + (\sigma_i^{\text{NP}})^2}}\right|$$

$\text{NP} - \text{II} \equiv$ NP scenario without NNC

LFU & V_{us} Observables

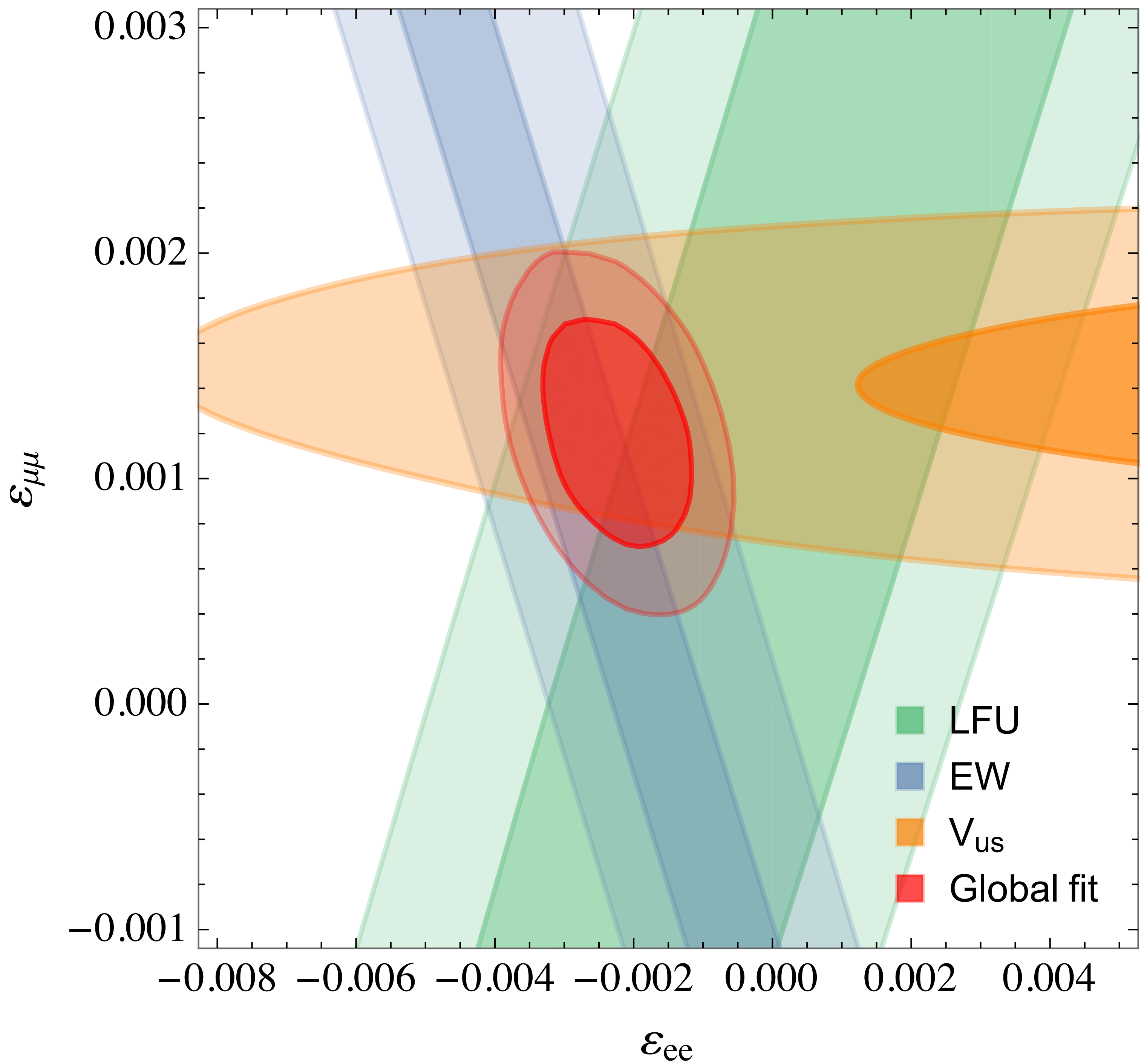
Observables included in the Model Independent global fit

Observable	Ref.	Measurement	SM Posterior	NP-II posterior	Pull II
$\frac{K\to\mu\nu}{K\to e\nu}$	[1, 14–16]	0.9978 ± 0.0020	1	1.00173 ± 0.00043	-0.82
$\frac{\pi\to\mu\nu}{\pi\to e\nu}$	[2, 3, 16–19]	1.0010 ± 0.0009	1	1.00173 ± 0.00043	0.38
$\frac{\tau\to\mu\nu\bar{\nu}}{\tau\to e\nu\bar{\nu}}$	[3, 4]	1.0018 ± 0.0014	1	1.00173 ± 0.00043	1.24
$\frac{K\to\pi\mu\bar{\nu}}{K\to\pi e\bar{\nu}}$	[1, 20, 21]	1.0010 ± 0.0025	1	1.00173 ± 0.00043	0.11
$\frac{W\to\mu\bar{\nu}}{W\to e\bar{\nu}}$	[1, 5]	0.996 ± 0.010	1	1.00173 ± 0.00043	-0.17
$\frac{B\to D^{(*)}\mu\nu}{B\to D^{(*)}e\nu}$	[6]	0.989 ± 0.012	1	1.00173 ± 0.00043	-0.14
$\frac{\tau\to e\nu\bar{\nu}}{\mu\to e\bar{\nu}\nu}$	[3, 4]	1.0010 ± 0.0014	1	0.9995 ± 0.0010	-0.15
$\frac{\tau\to\pi\nu}{\pi\to\mu\bar{\nu}}$	[4]	0.9961 ± 0.0027	1	0.9995 ± 0.0010	0.26
$\frac{\tau\to K\nu}{K\to\mu\bar{\nu}}$	[4]	0.9860 ± 0.0070	1	0.9995 ± 0.0010	0.09
$\frac{W\to\tau\bar{\nu}}{W\to\mu\bar{\nu}}$	[1, 5]	1.034 ± 0.013	1	0.9995 ± 0.0010	-0.03
$\frac{\tau\to\mu\nu\bar{\nu}}{\mu\to e\nu\bar{\nu}}$	[3, 4]	1.0029 ± 0.0014	1	1.0013 ± 0.0011	1.17
$\frac{W\to\tau\bar{\nu}}{W\to e\bar{\nu}}$	[1, 5]	1.031 ± 0.013	1	1.0013 ± 0.0011	0.11
$\lvert V_{us}^{K_{\mu3}}\rvert$	[3, 22]	0.2234 ± 0.0008	0.2257(3)	0.22516 ± 0.00040	0.74
$\lvert V_{us}/V_{ud}\rvert^{K/\pi}$	[22, 23]	0.2313 ± 0.0005	0.2317(4)	0.23082 ± 0.00044	-0.10
$\lvert V_{us}^{\tau}\rvert_{\text{incl.}}$	[24, 25]	0.2195 ± 0.0019	0.2257(3)	0.22491 ± 0.00041	0.45
$\lvert V_{ud}^{\beta}\rvert_{\text{CMS}}$	[24, 25]	0.97389 ± 0.00018	0.974185(79)	-	-
$\lvert V_{ud}^{\beta}\rvert_{\text{SGPR}}$	[24, 26]	0.97370 ± 0.00014	0.974185(79)	0.97379 ± 0.00013	2.57

$$P(O_i) = \left| \frac{O_i^{\text{exp}} - O_i^{\text{SM}}}{\sqrt{(\sigma_i^{\text{exp}})^2 + (\sigma_i^{\text{SM}})^2}} \right| - \left| \frac{O_i^{\text{exp}} - O_i^{\text{NP}}}{\sqrt{(\sigma_i^{\text{exp}})^2 + (\sigma_i^{\text{NP}})^2}} \right|$$

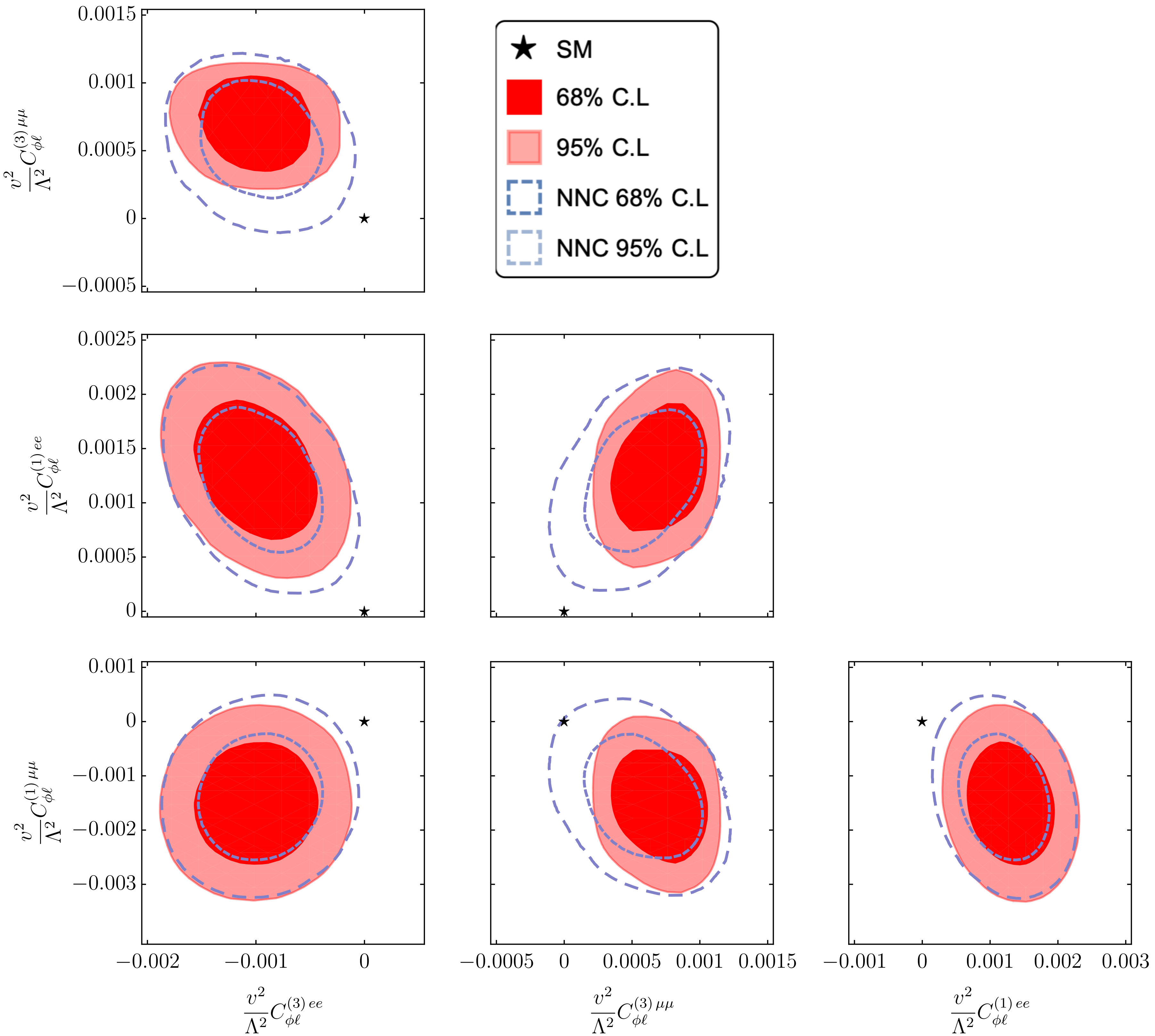
$\text{NP} - \text{II} \equiv$ NP scenario without NNC

Contributions to the Fit

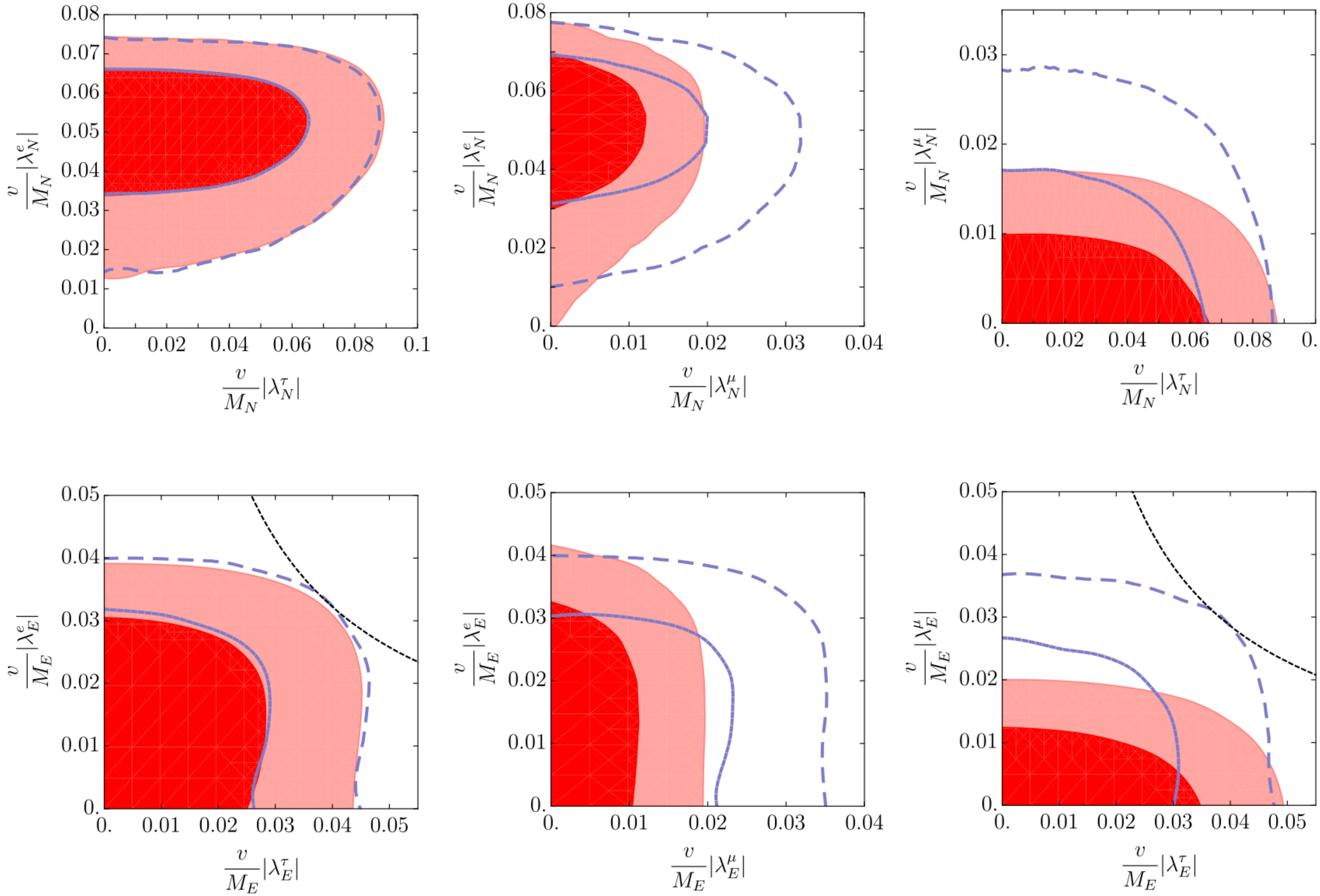


Contributions to the global fit from each class of observables. 1σ and 2σ regions are shown in the ϵ_{ee} vs $\epsilon_{\mu\mu}$ plane, marginalising over $\epsilon_{\tau\tau}$.

$C^{(3)}_{\phi\ell}$ vs $C^{(1)}_{\phi\ell}$ - 4D plot



N and E bounds



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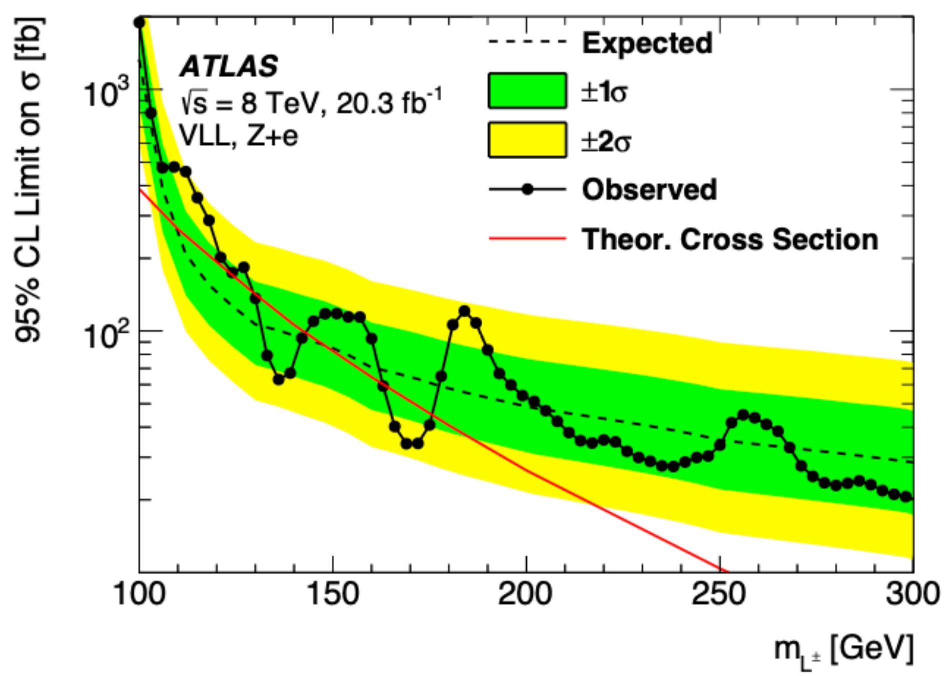
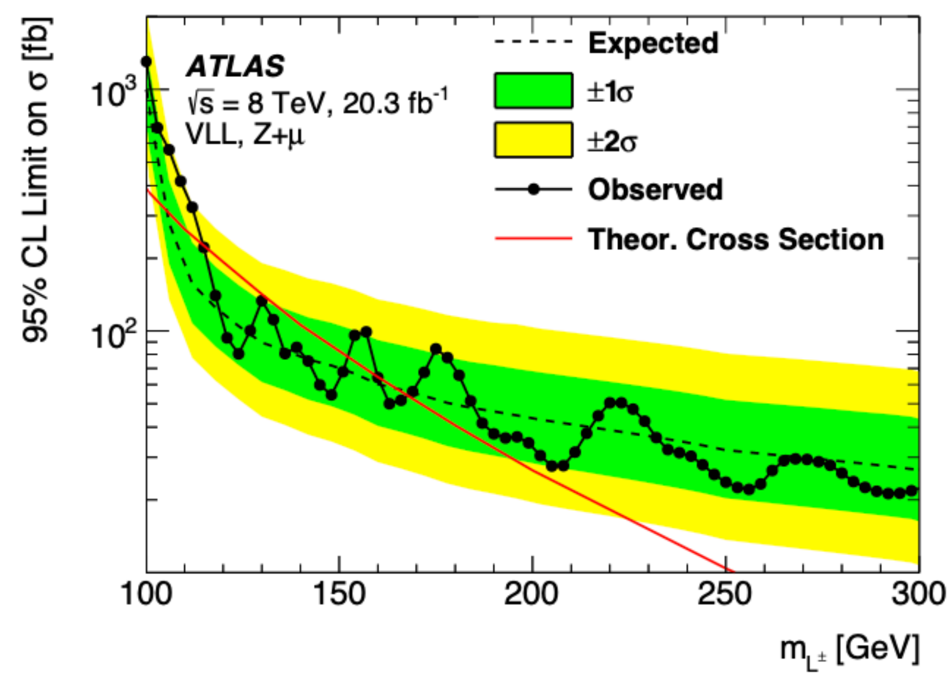
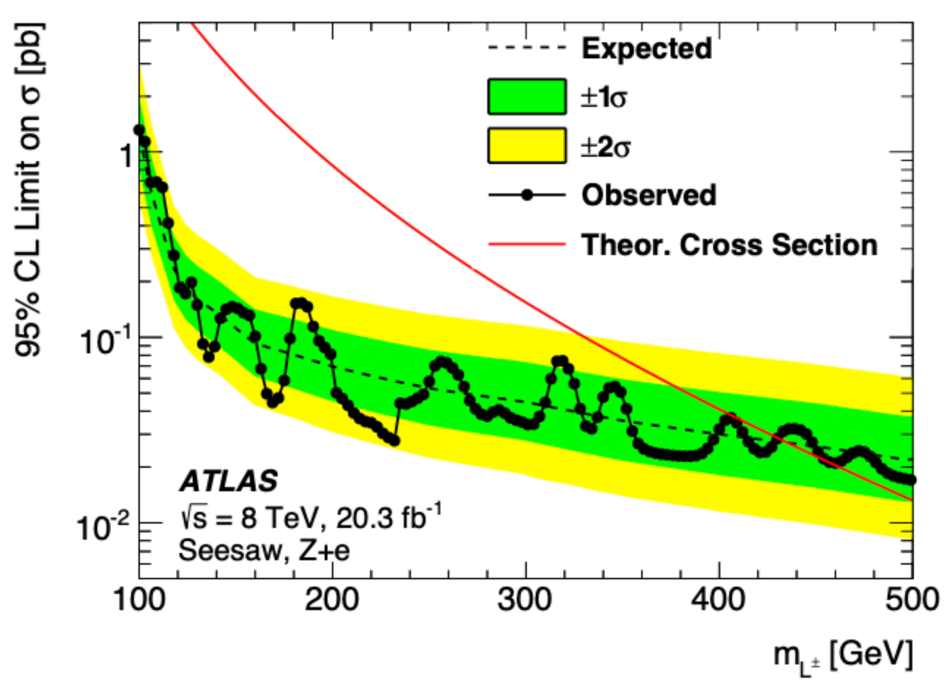
LHC bounds for the Vector-Like Leptons

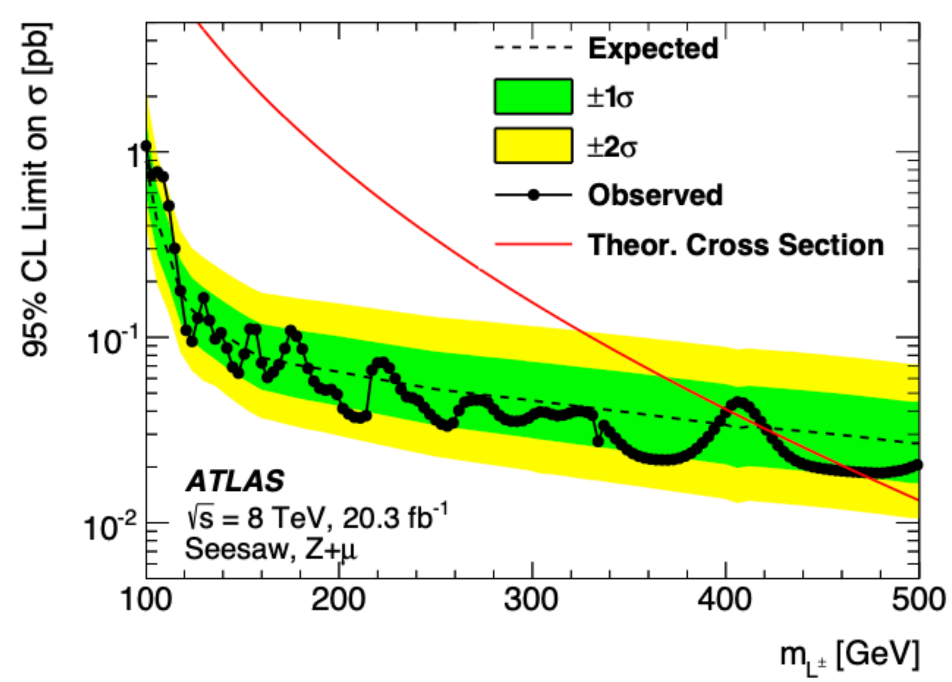
N





Σ_0





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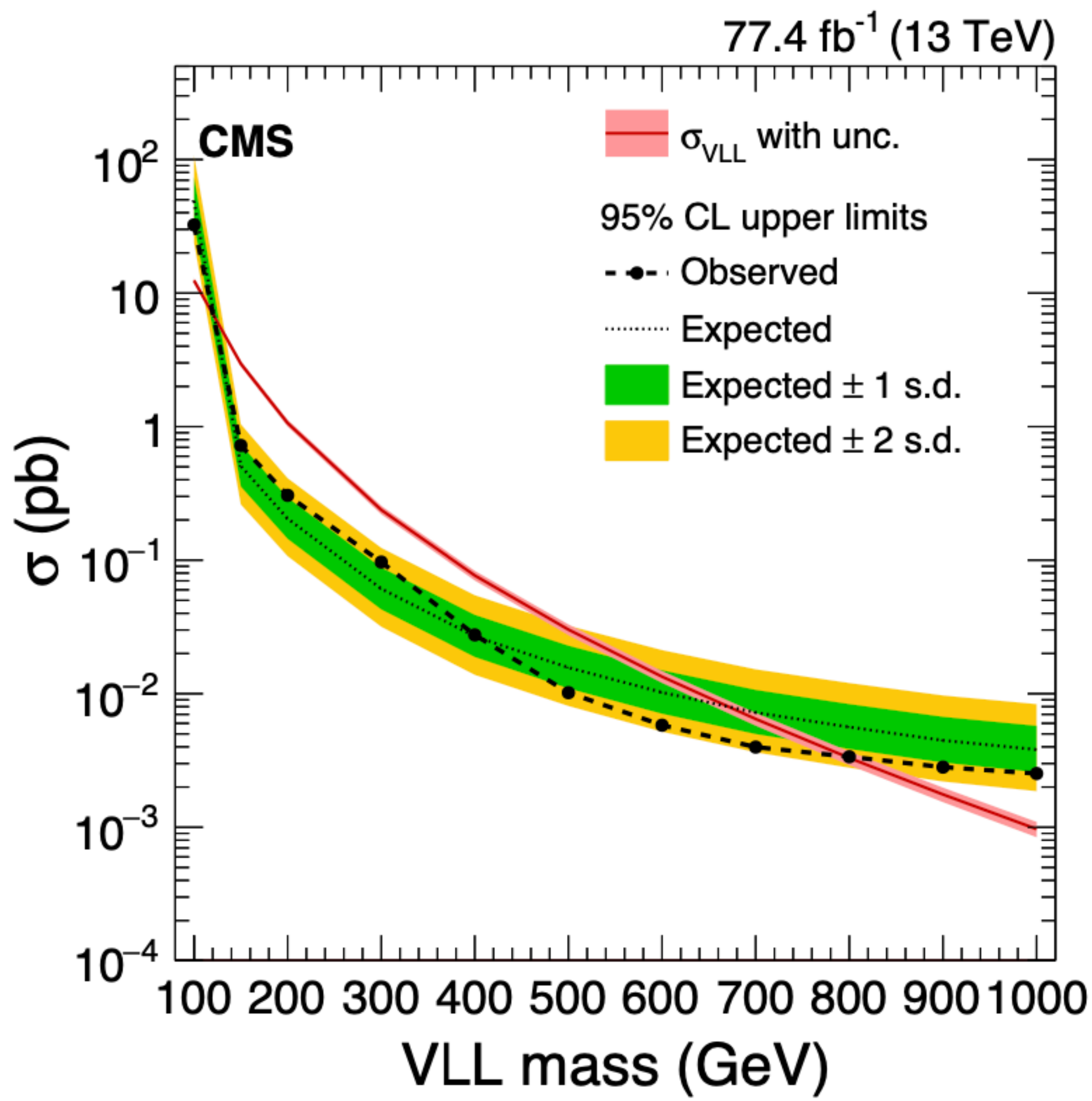
LHC bounds for the Vector-Like Leptons

Δ_1



University of Zurich

Information Criterion

In a bayesian approach, the *Information Criterion* allows for a comparison between different models

$$IC = -2\log L + 4\sigma^2_{\log L}$$

average of the log-likelihood

variance of the log-likelihood

The second term takes into account the effective numbers of parameters in the model, allowing for a meaningful comparison of models with different number of parameters. Preferred models are expected to give smaller *IC* values

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