The Cabibbo-Angle Anomaly (and $b \to s\ell^+\ell^-$)

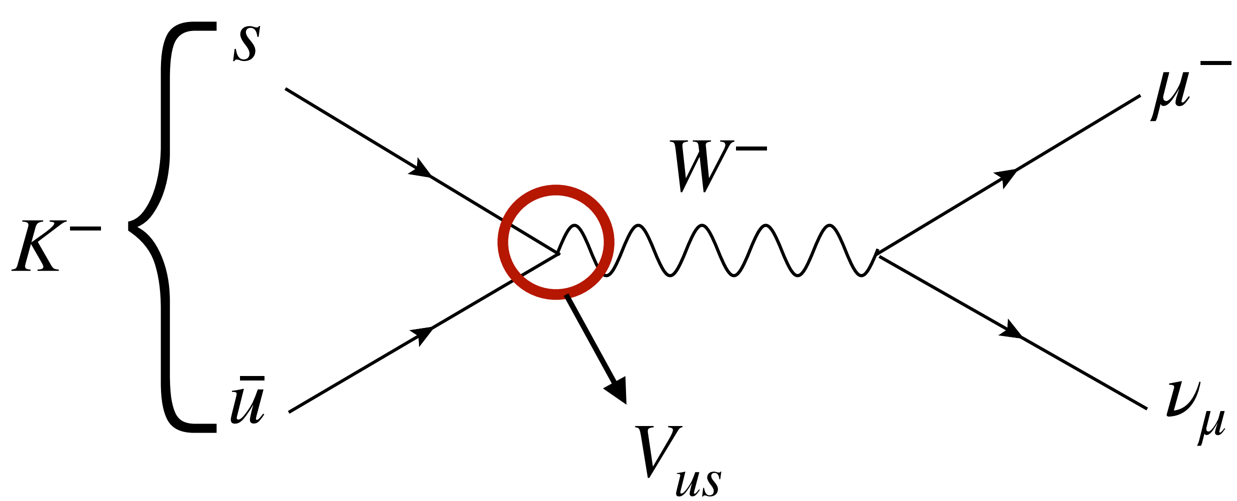
Claudio Andrea Manzari

based on: 1912.08823

preliminary work of B.Capdevila, A.Crivellin, C.A.Manzari, M.Montull

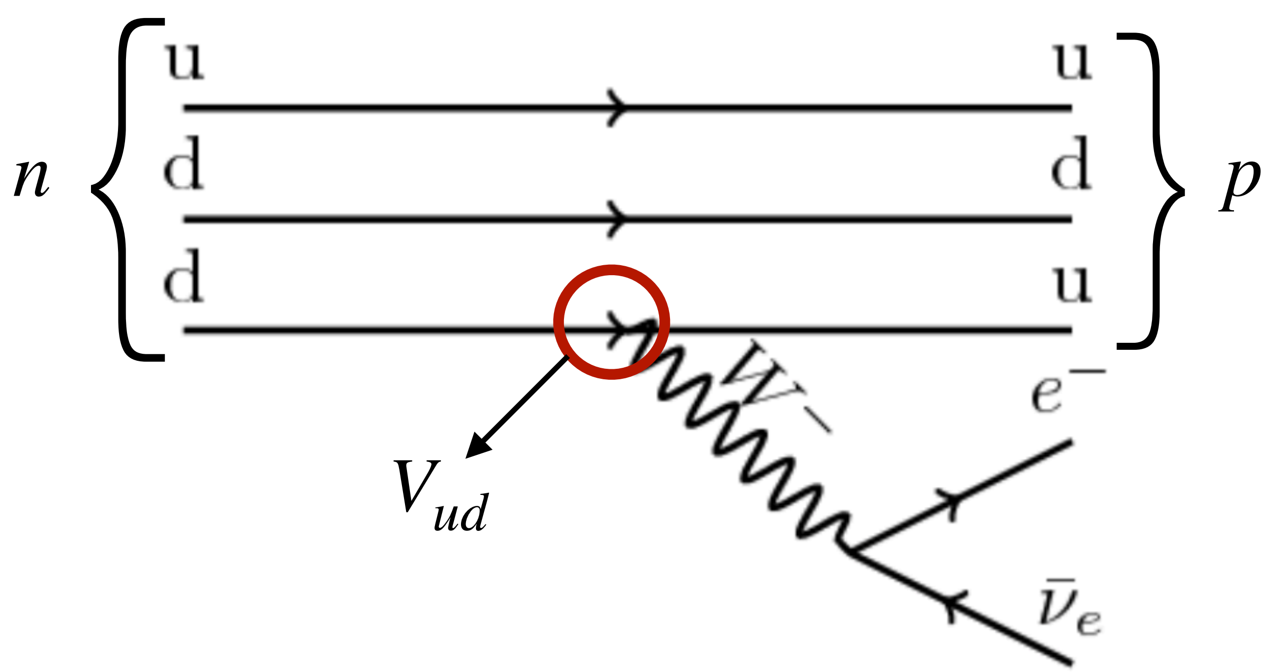
The CKM matrix

The unitary Cabibbo-Kobayashi-Maskawa (CKM) matrix parametrize the misalignment between the up- and down-quark Yukawa couplings in the physical basis with diagonal mass matrices.

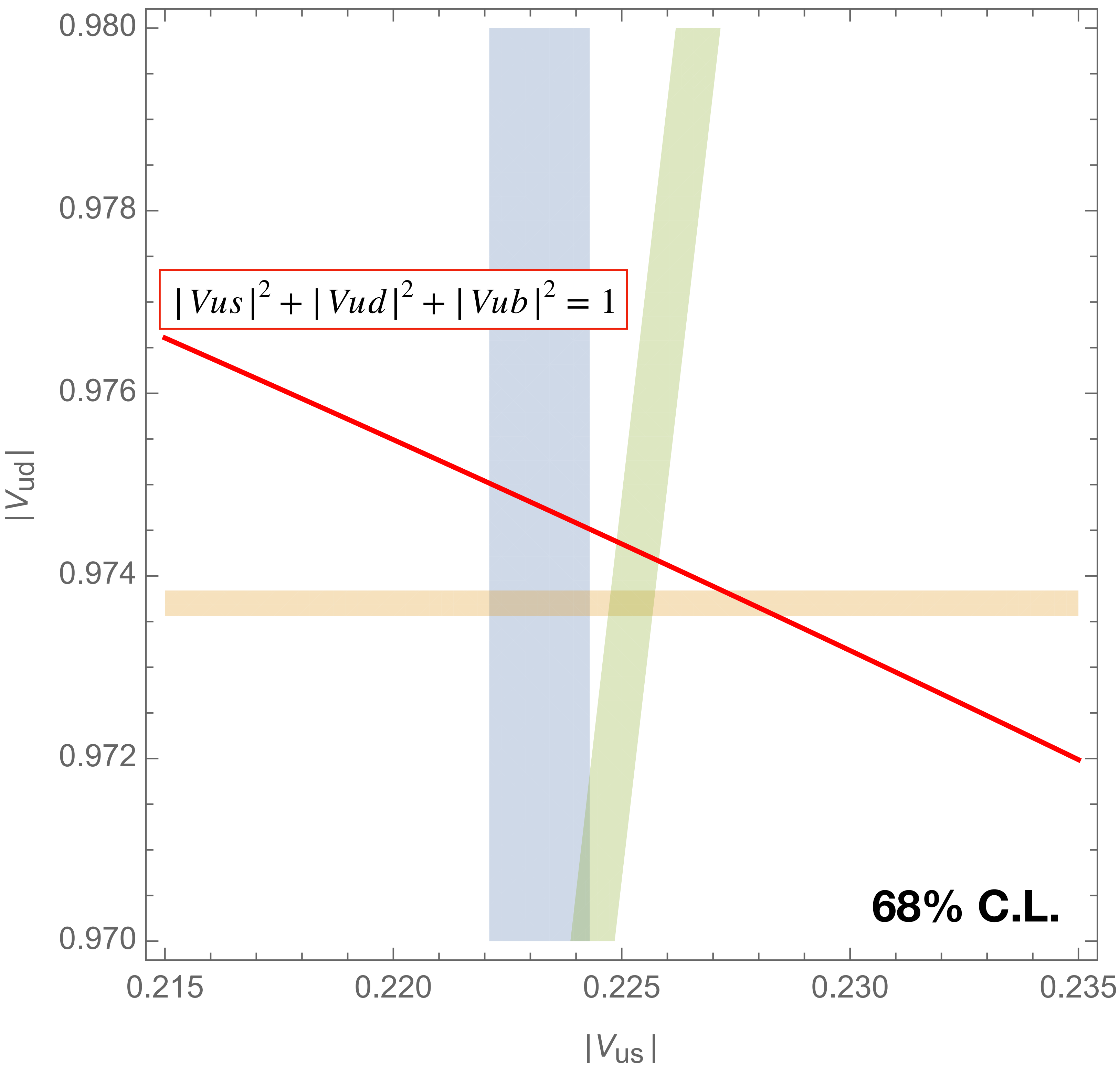


$$|Vud|^2 + |Vus|^2 + |Vub|^2 = 1$$

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



The Anomaly



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

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

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

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

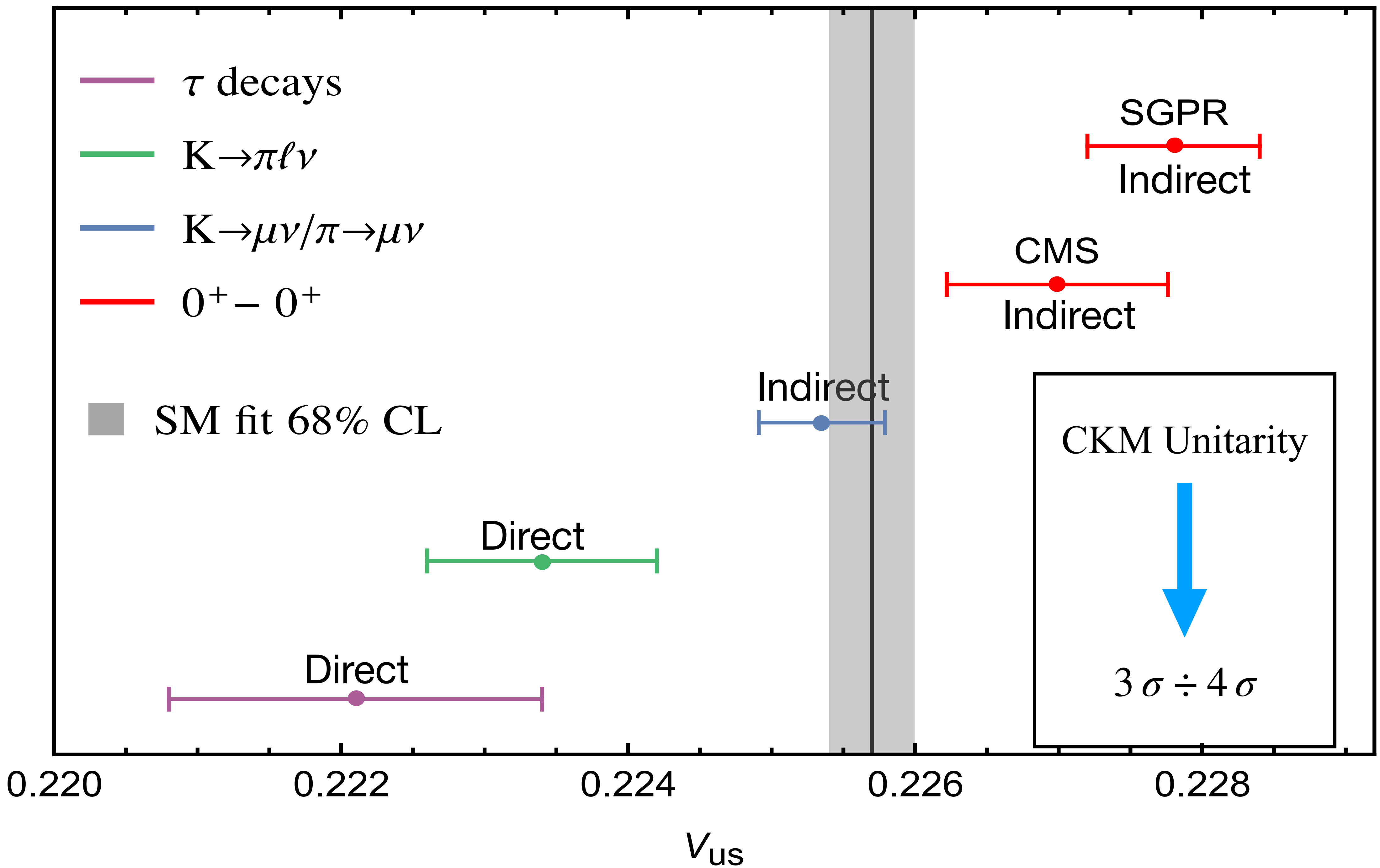
- $0^+ - 0^+$ + corrections

$$|V_{ud}|_{CMS} = 0.97389(18)$$

$$|V_{ud}|_{SGPR} = 0.97370(14)$$

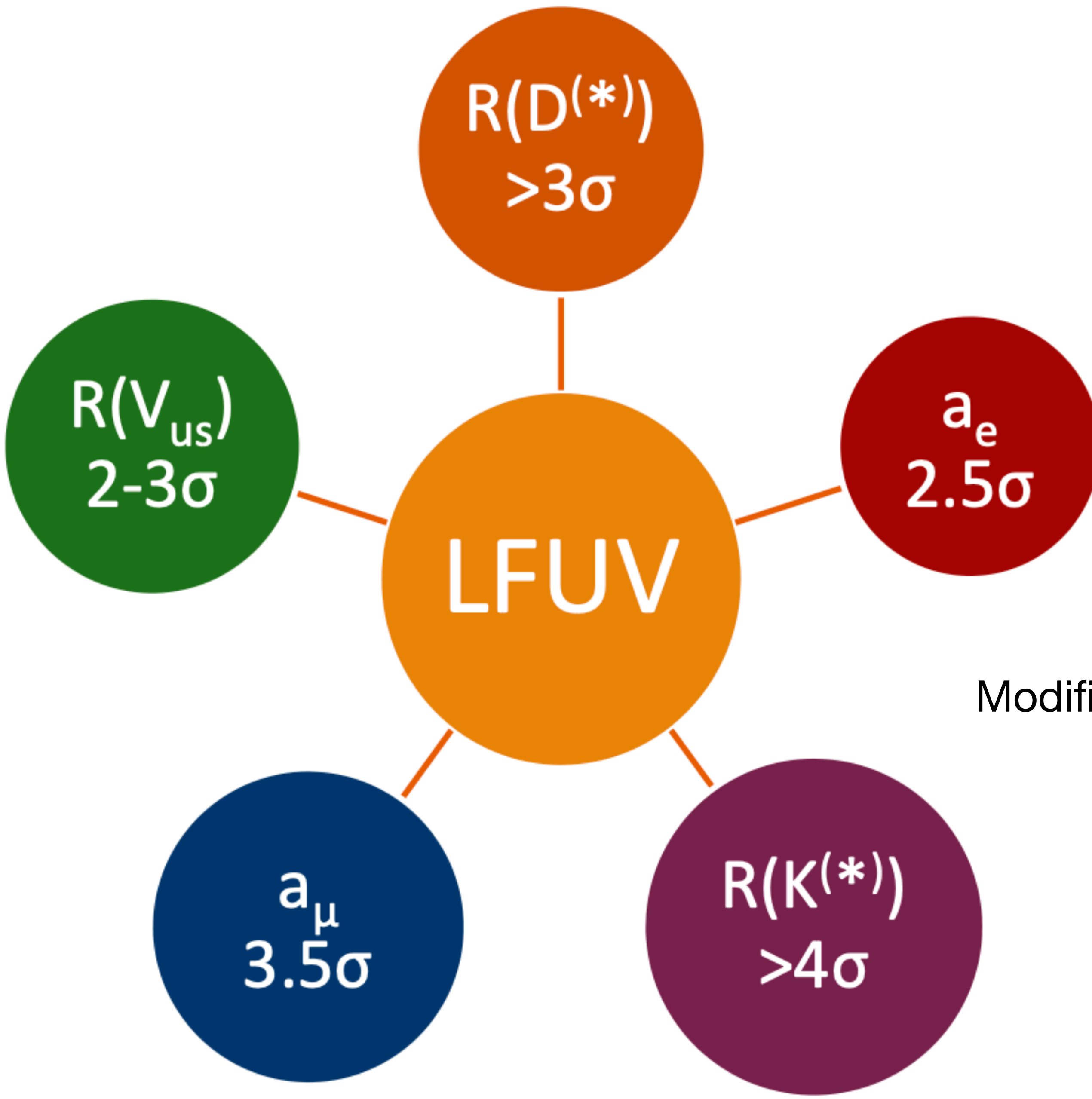
The Anomaly

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



LFUV

$R(V_{us}) = \frac{V_{us}^{K_{\mu 2}}}{V_{us}^{\beta}}$ as a test of LFUV complements to an already interesting picture



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

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

Modification of the coupling of the W with muons

Modified Neutrino Couplings

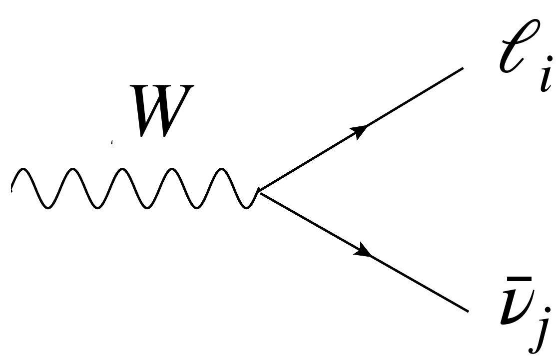
Minimal impact: **we modify only the couplings of W and Z with neutrinos**

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

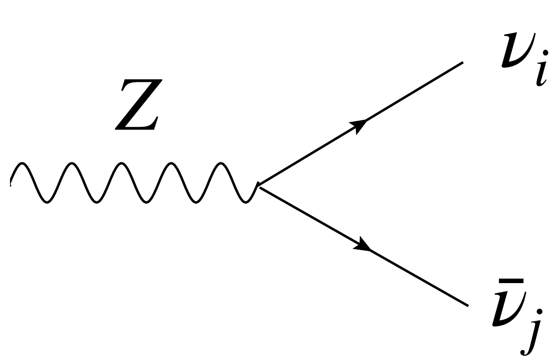
dim = 6

There is 1 Operator which modifies only neutrino couplings :

$$\bar{L}_i \gamma_\mu \tau^I L_j H^\dagger i D_I^\mu H \quad \text{with} \quad \tau^I = (1\,, -\sigma_1\,, -\sigma_2\,, -\sigma_3)$$



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



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

University of Zurich[UZH]

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.

Neglected in what follows

PAUL SCHERRER INSTITUT

PSI

Parameters and Observables

University of Zurich

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} Observables

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

$$|V_{us}^{\tau\to K\nu}| \approx |V_{us}^{\mathcal{L}}|\left(1 - \frac{1}{2}\varepsilon_{ee} - \frac{1}{2}\varepsilon_{\mu\mu} + \frac{1}{2}\varepsilon_{\tau\tau}\right)$$

Not affected

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

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

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

PAUL SCHERRER INSTITUT PSI

University of Zurich[UZH]

Parameters and Observables

Low Energy Observables

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

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

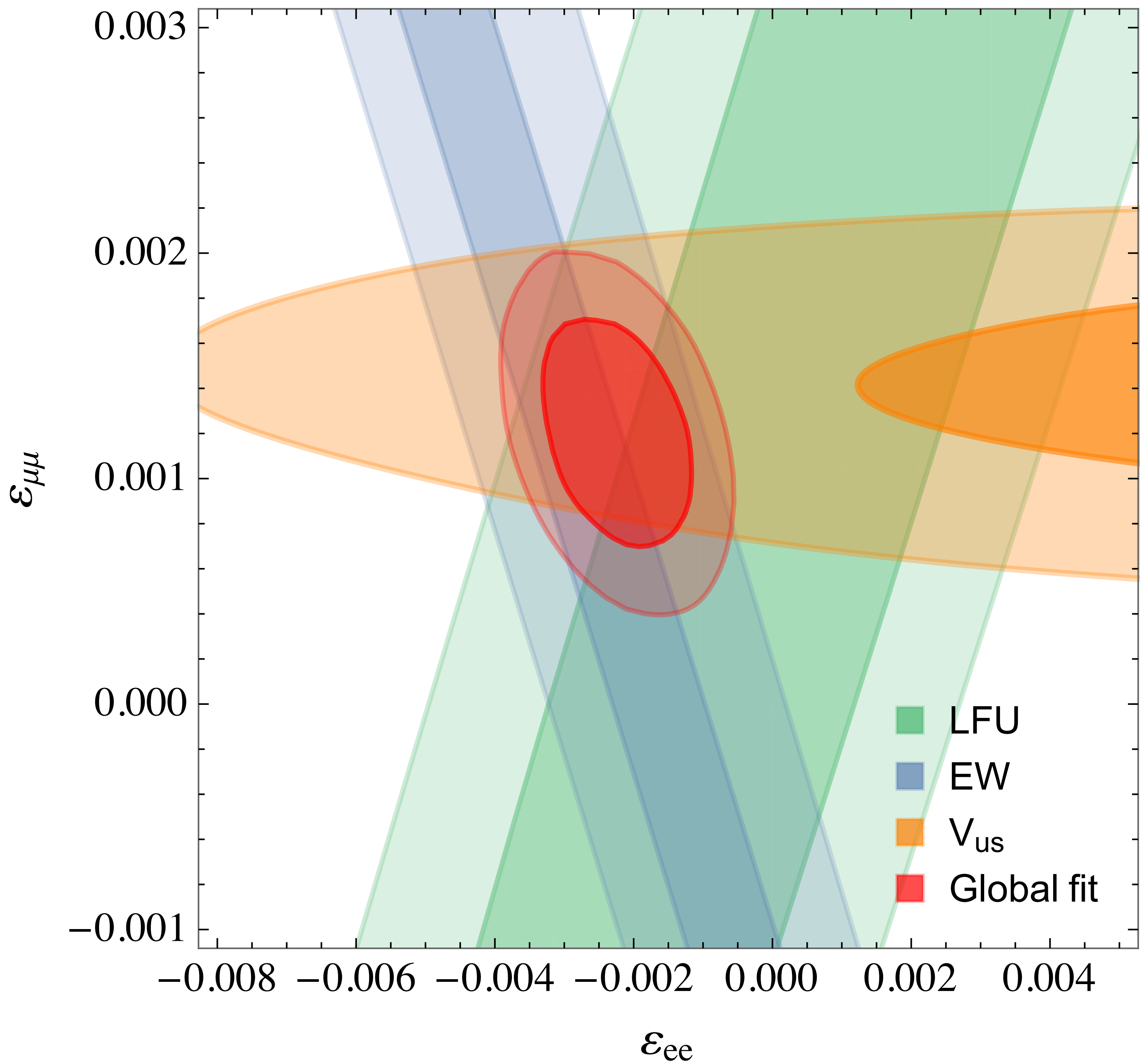
$$\frac{\tau\to e\nu\nu}{\mu\to e\nu\nu} \sim \left.\frac{\tau\to e\nu\nu}{\mu\to e\nu\nu}\right|_{\rm SM} (1+\frac{1}{2}\epsilon_{\tau\tau}-\frac{1}{2}\epsilon_{\mu\mu}) \quad \left\{ \begin{matrix} \frac{\tau\to\pi\nu}{\pi\to\mu\nu} & \frac{\tau\to K\nu}{K\to\mu\nu} \\ \multicolumn{2}{c}{\frac{W\to\tau\nu}{W\to\mu\nu}}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

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

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

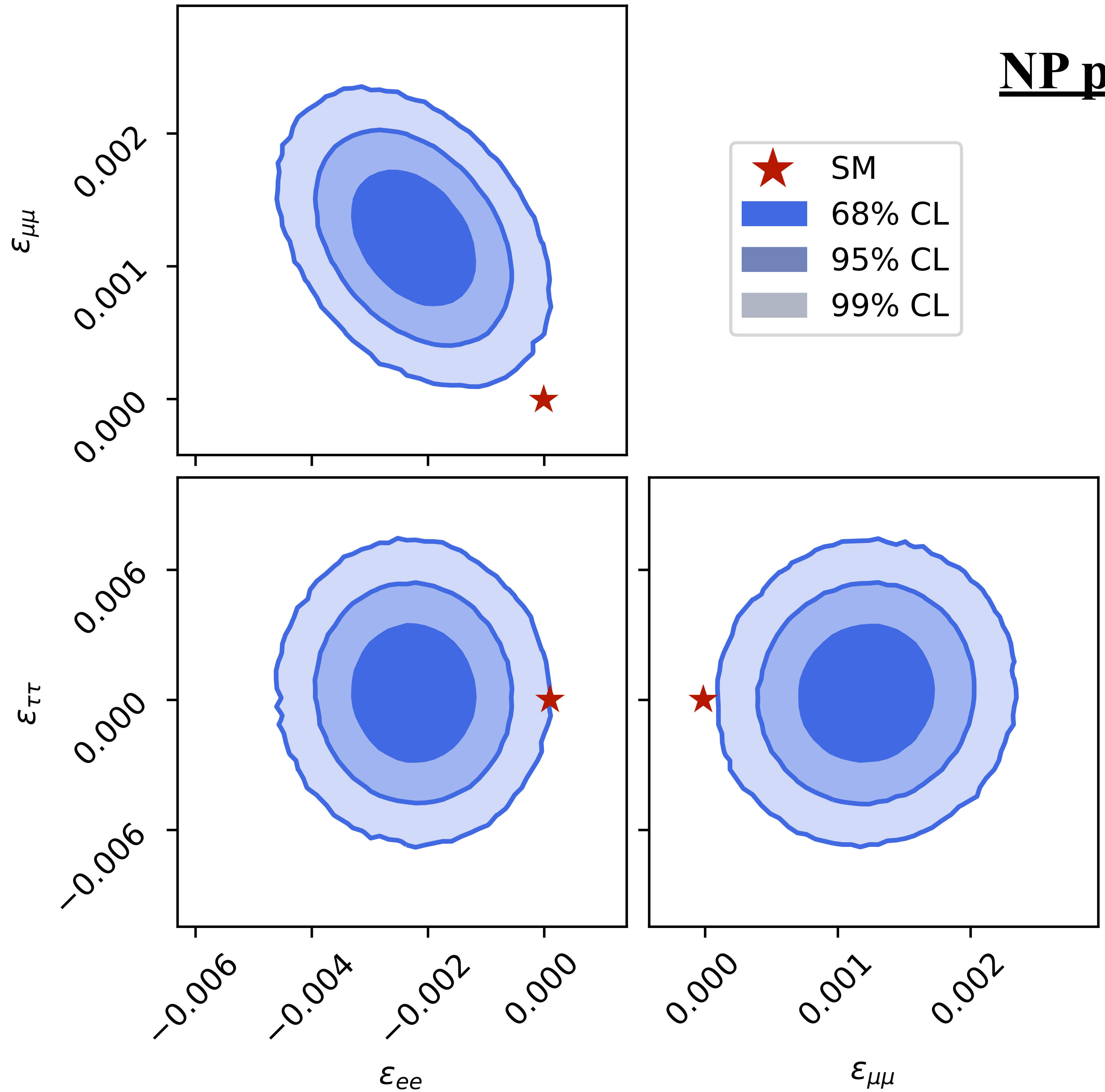
PAUL SCHERRER INSTITUT PSI

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 $\epsilon_{\tau\tau}$.

Global Fit



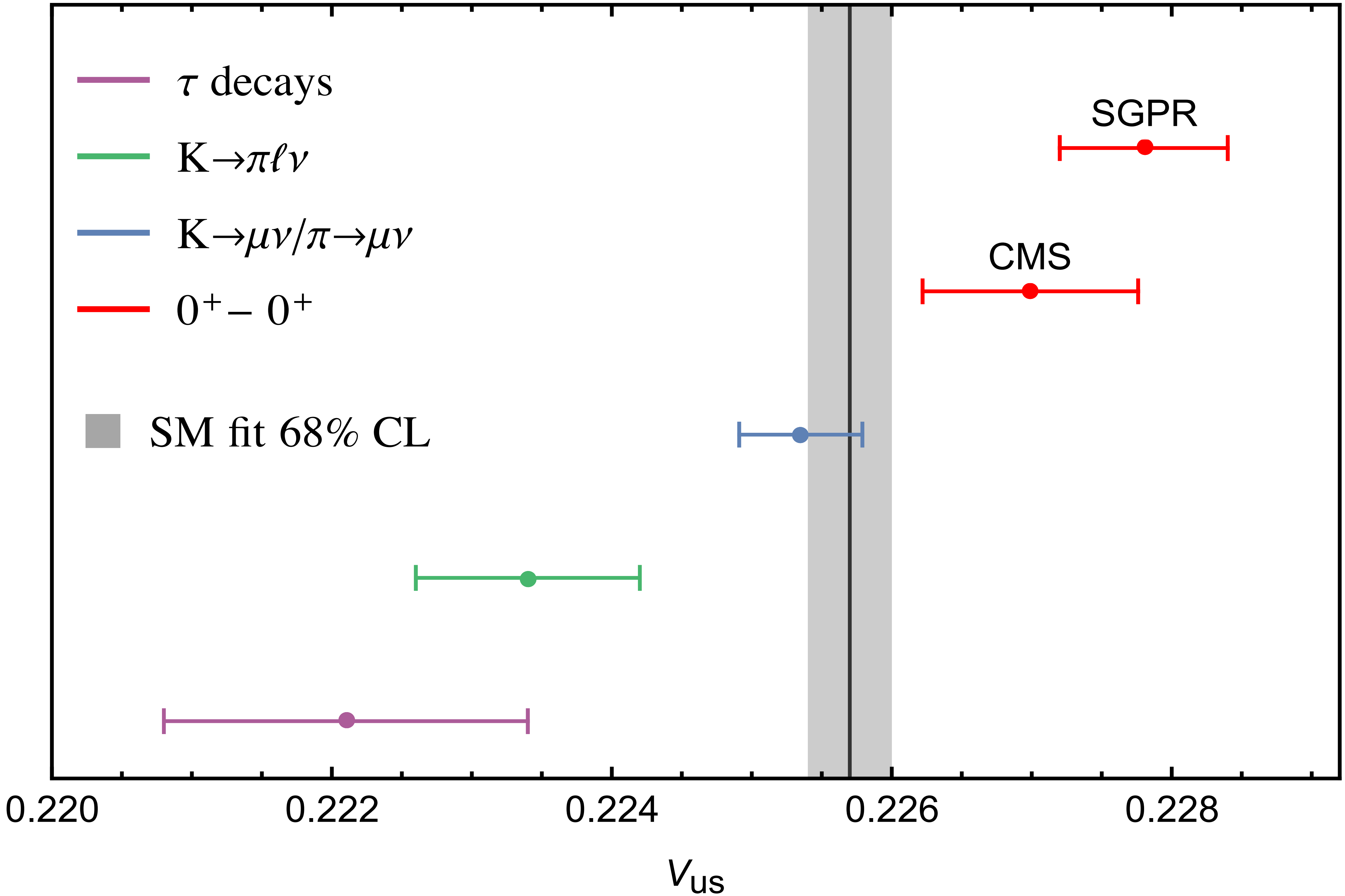
<u>NP preferred</u> at more than 99% C.L.

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

$\mathrm{IC}_{\mathrm{NP}} \simeq 63$

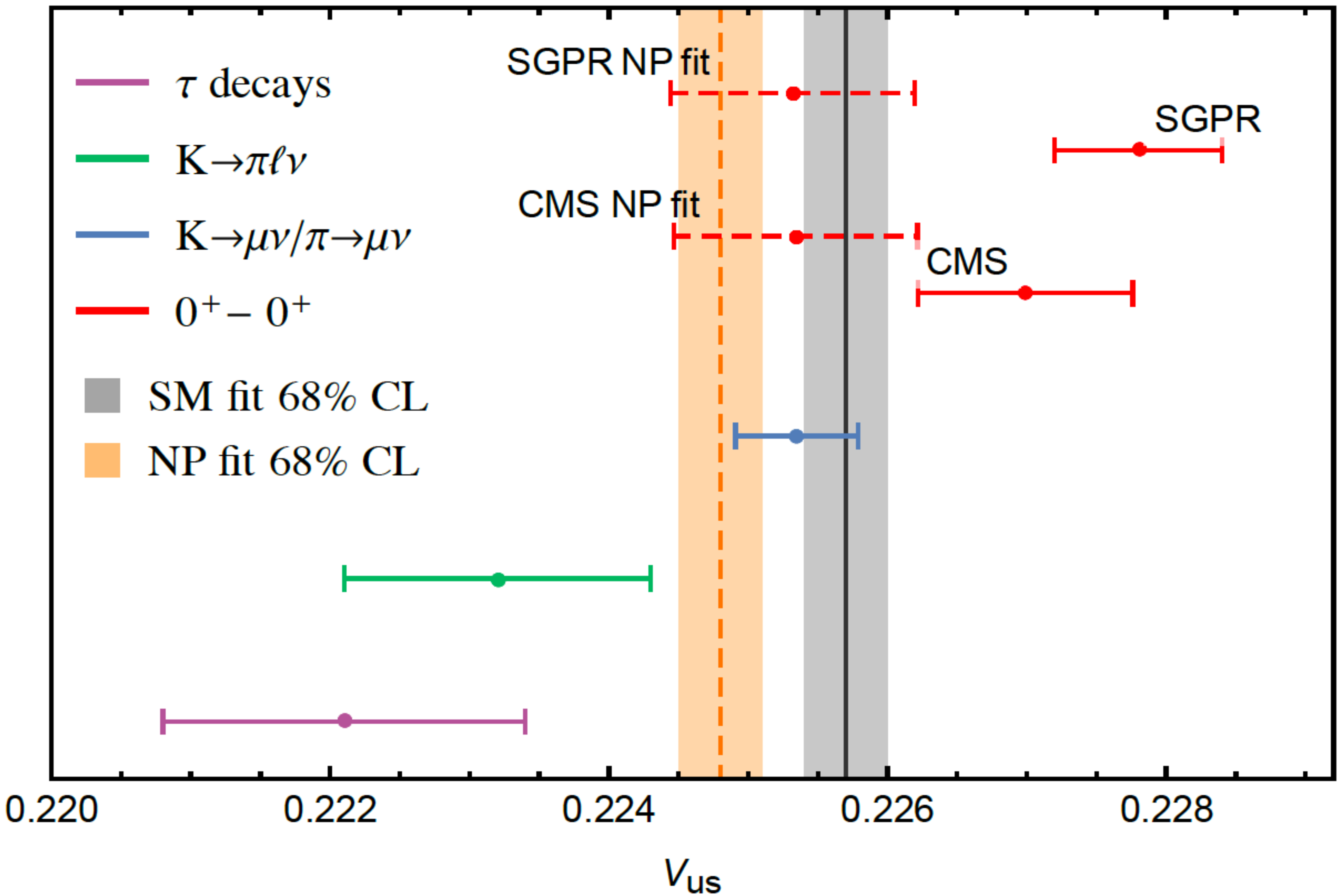
HEPfit

Global Fit



τ decays
K→πℓν
K→μν/π→μν
0⁺– 0⁺
SM fit 68% CL
SGPR
CMS
0.220
0.222
0.224
0.226
0.228
V_us

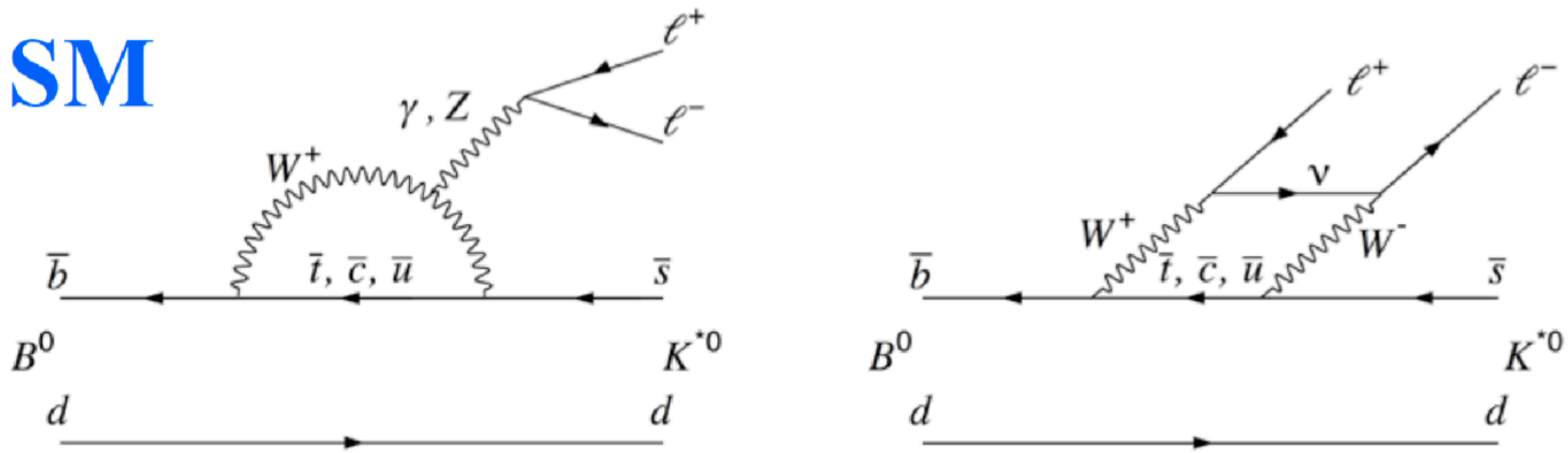
Global Fit



τ decays
K→πℓν
K→μν/π→μν
0⁺– 0⁺
SM fit 68% CL
NP fit 68% CL
SGPR NP fit
SGPR
CMS NP fit
CMS
0.220
0.222
0.224
0.226
0.228
Vus

Combining CAA with $b \to s\ell\ell$

Many observables related to the flavour-changing neutral-current transition $b \to s\ell^+\ell^-$ exhibit deviations from SM expectations.



Due to their suppression in the SM, they have a high sensitivity to potential NP contributions.

To perform a global fit to all the data we work within the model-independent approach of the effective Hamiltonian:

$$H_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i C_i O_i$$

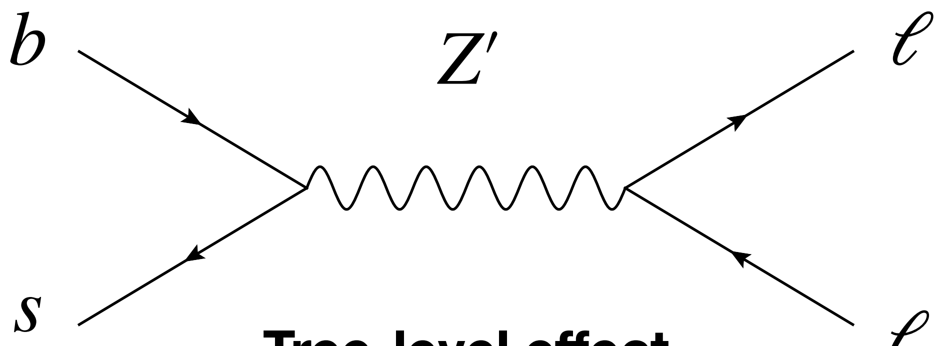
$$O_9 = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma_\mu \ell)$$

$$O_{10} = \frac{e^2}{16\pi^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma_\mu \gamma_5 \ell)$$

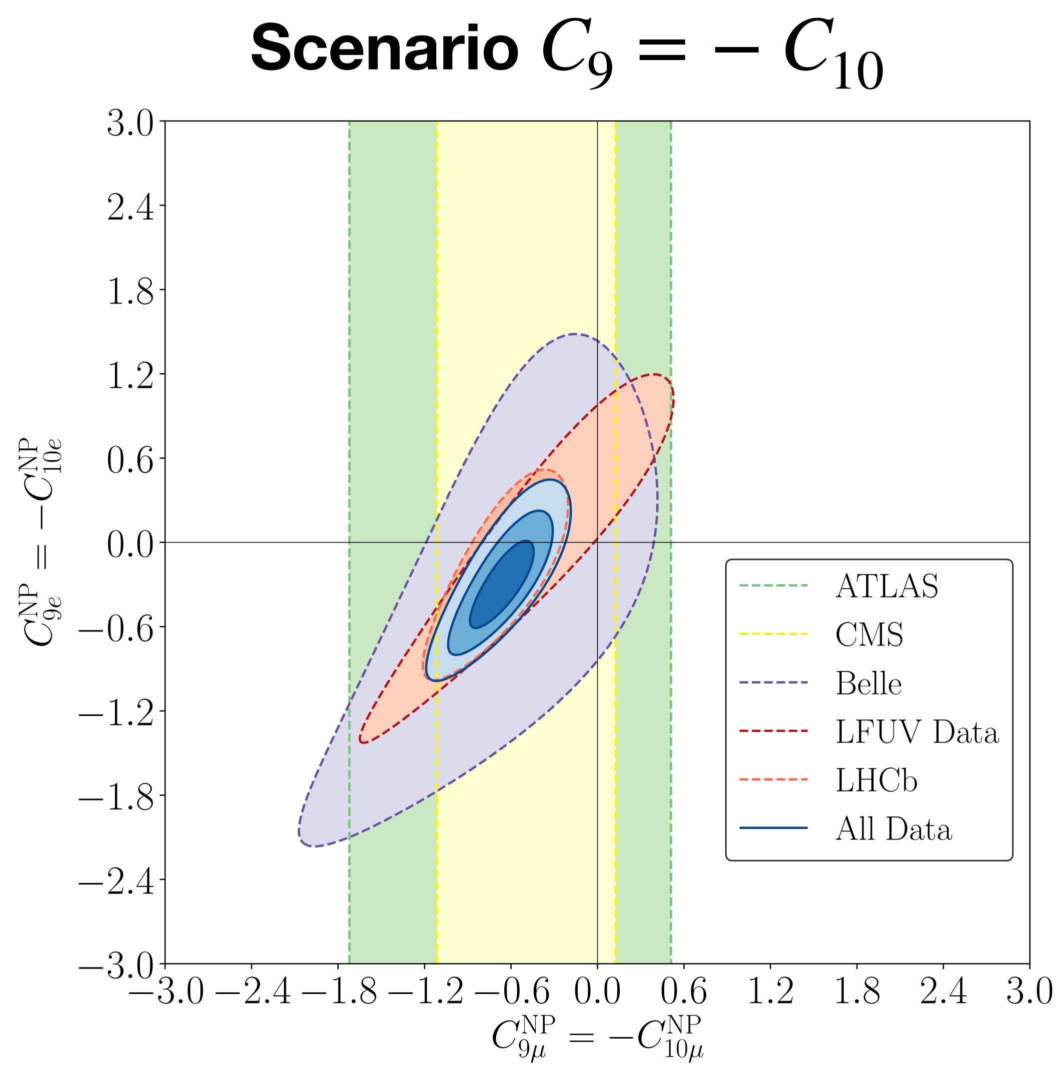
Z' and W'

Z' models provide a promising solution to $b \to s\ell\ell$, but we need:

1. flavour violating couplings to quarks;
2. non-universal couplings to leptons;



Tree-level effect

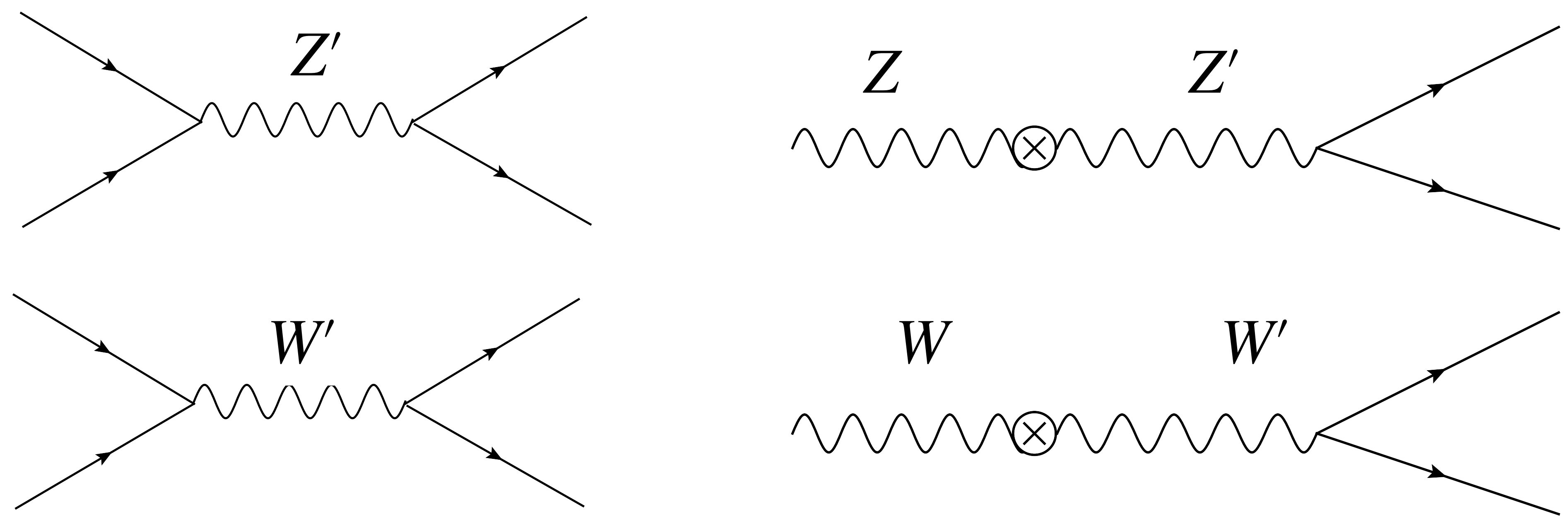


Is there a correlation between the Cabibbo Angle Anomaly and $b \to s\ell\ell$?

Prompted by the Z', we can attempt to solve **the CAA anomaly with a** W'

The Vector Triplet Model

A new heavy Vector Triplet coupling to left-handed fermions provides an interesting solution



Deeper impact: **modified W and Z couplings & direct effects from W' and Z'**

- EW observables
- Low energy observables (K, π, τ, W decays)
- $b \to s\ell\ell$

The Vector Triplet Model

$$\mathcal{L}_X^{\rm int} = -\, g_{ji}^{\ell} X_a^{\mu} \bar{\ell}_j \gamma_\mu \frac{\sigma^a}{2} \ell_i - g_{ji}^{q} X_a^{\mu} \bar{q}_j \gamma_\mu \frac{\sigma^a}{2} q_i - \left(i g_X^{D\phi} X_a^{\mu} \phi^\dagger \frac{\sigma^a}{2} D_\mu \phi + \mathrm{h.c.} \right)$$

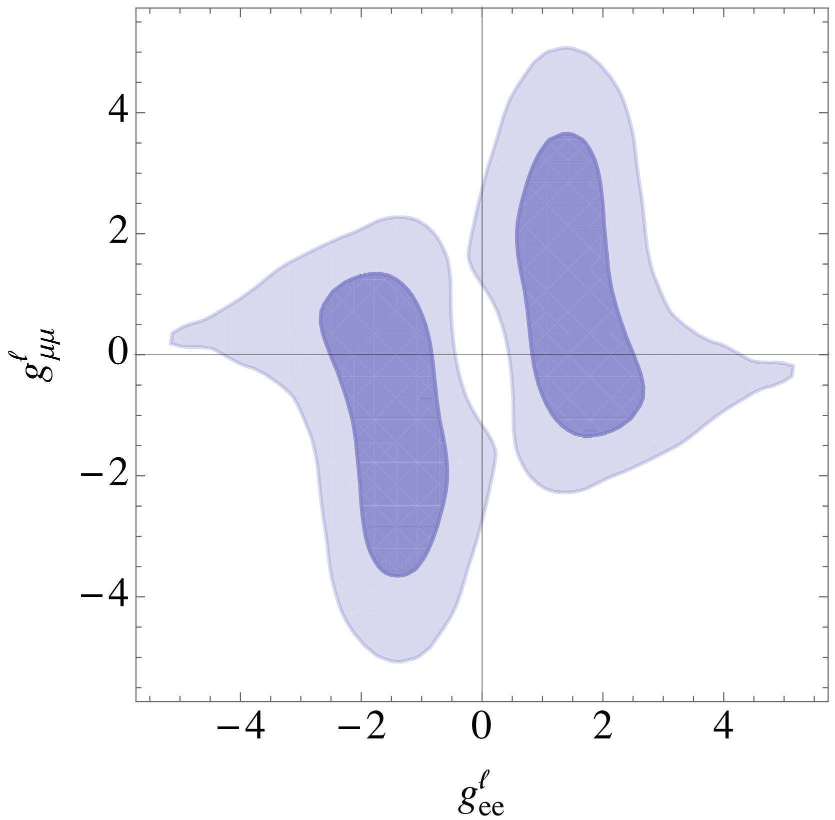
NP Parameters : $g_{ee}^{\ell}, \quad g_{\mu\mu}^{\ell}, \quad g_{\tau\tau}^{\ell}, \quad g^{q}, \quad g_X^{D\phi}$

EW Parameters : $G_F, \quad \alpha, \quad M_Z$

$$M_Z^{\rm exp} = M_Z^{\mathcal{L}} \sqrt{\left(1 - \frac{|g_X^{D\phi}|^2 v^2}{4 M_X^2} \right)}$$

$$G_F^{\rm exp} = G_F^{\mathcal{L}} \left(1 + \frac{g_X^{D\phi}(g_{11}^{\ell} + g_{22}^{\ell}) v^2}{2 M_X^2} \right) + \frac{g_{11}^{\ell} g_{22}^{\ell}}{4\sqrt{2} M_X^2}$$

EW+LFU+V_{us}

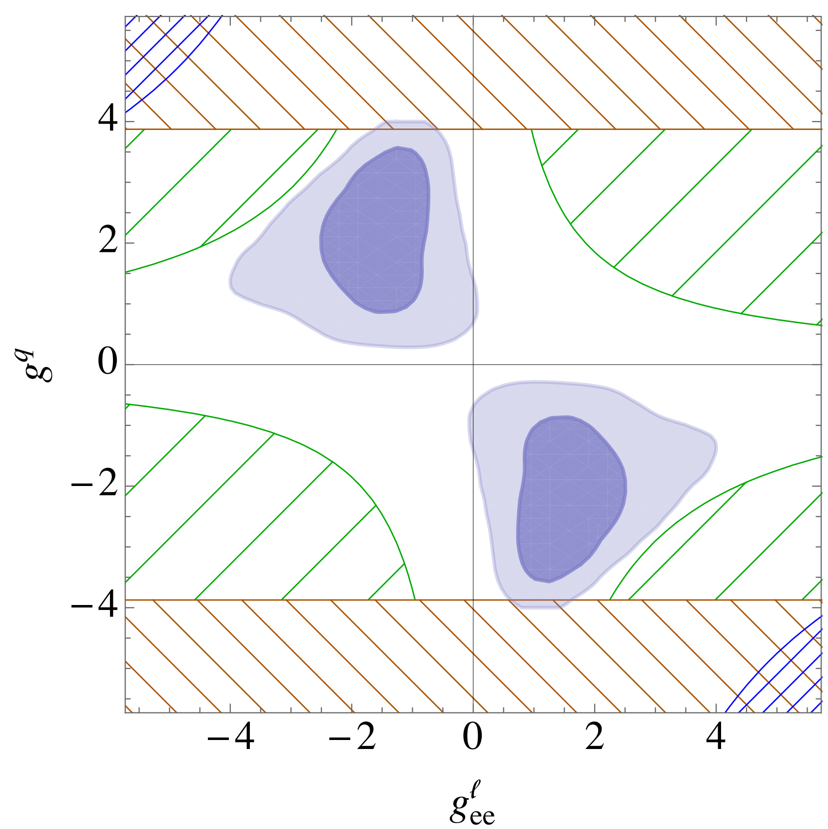


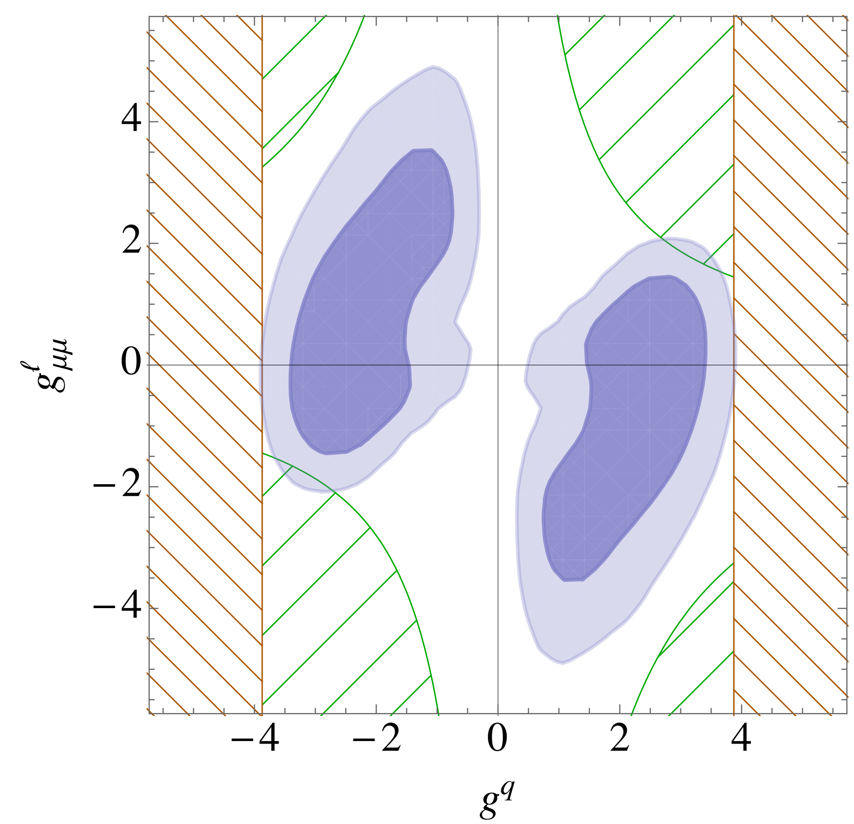
$IC_{SM} \simeq 110.61$

$IC_{NP} \simeq 96.453$

- EW+V_{us}+LFU 68% CL
- EW+V_{us}+LFU 95% CL
- QWEAK excluded 68% CL
- LHC−dilepton excluded 95% CL
- LHC−dijet excluded 95% CL

Preliminary

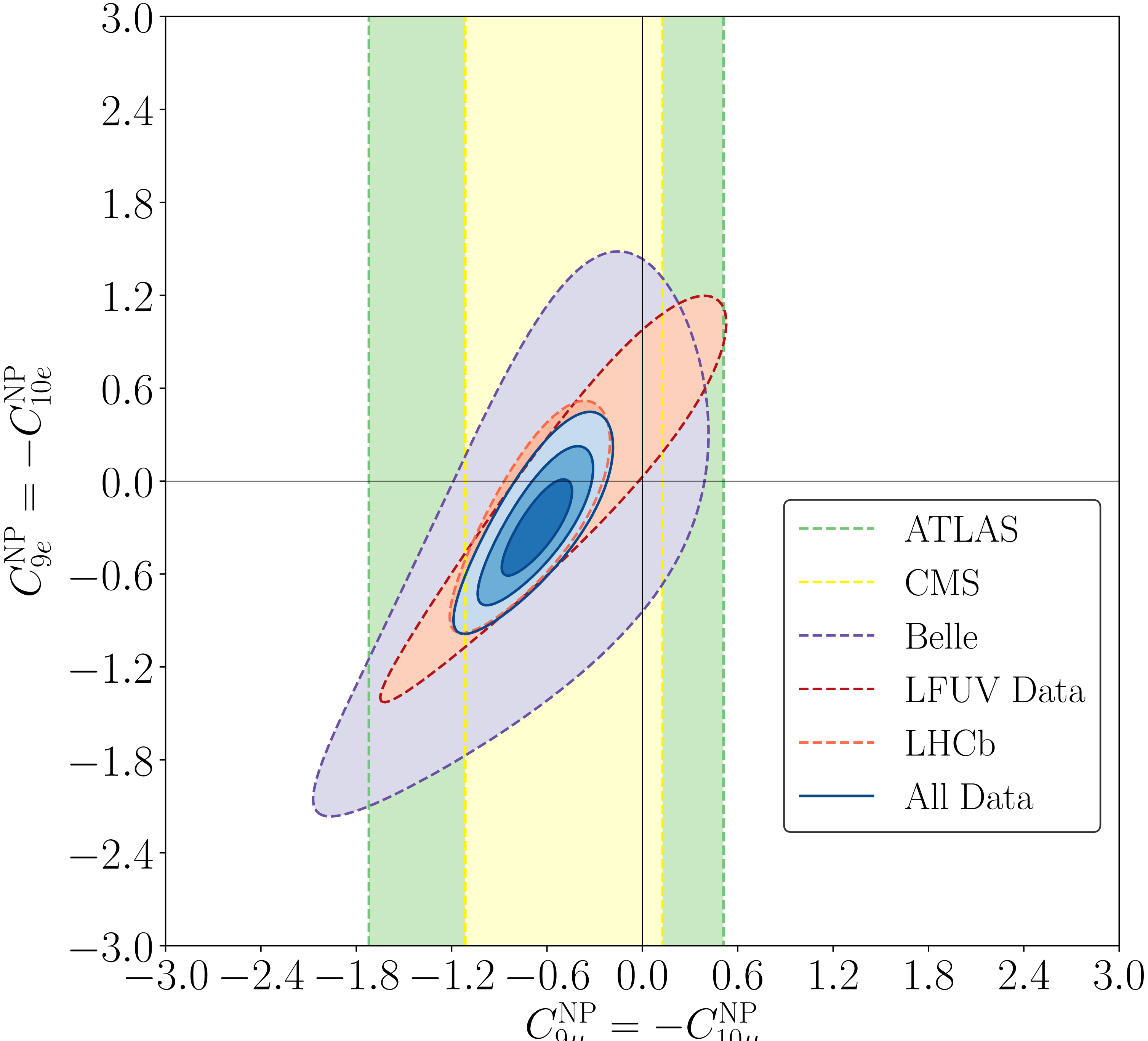




$b \to s\ell\ell$

Is there a connection between the Cabibbo Angle Anomaly and $b \to s\ell\ell$?

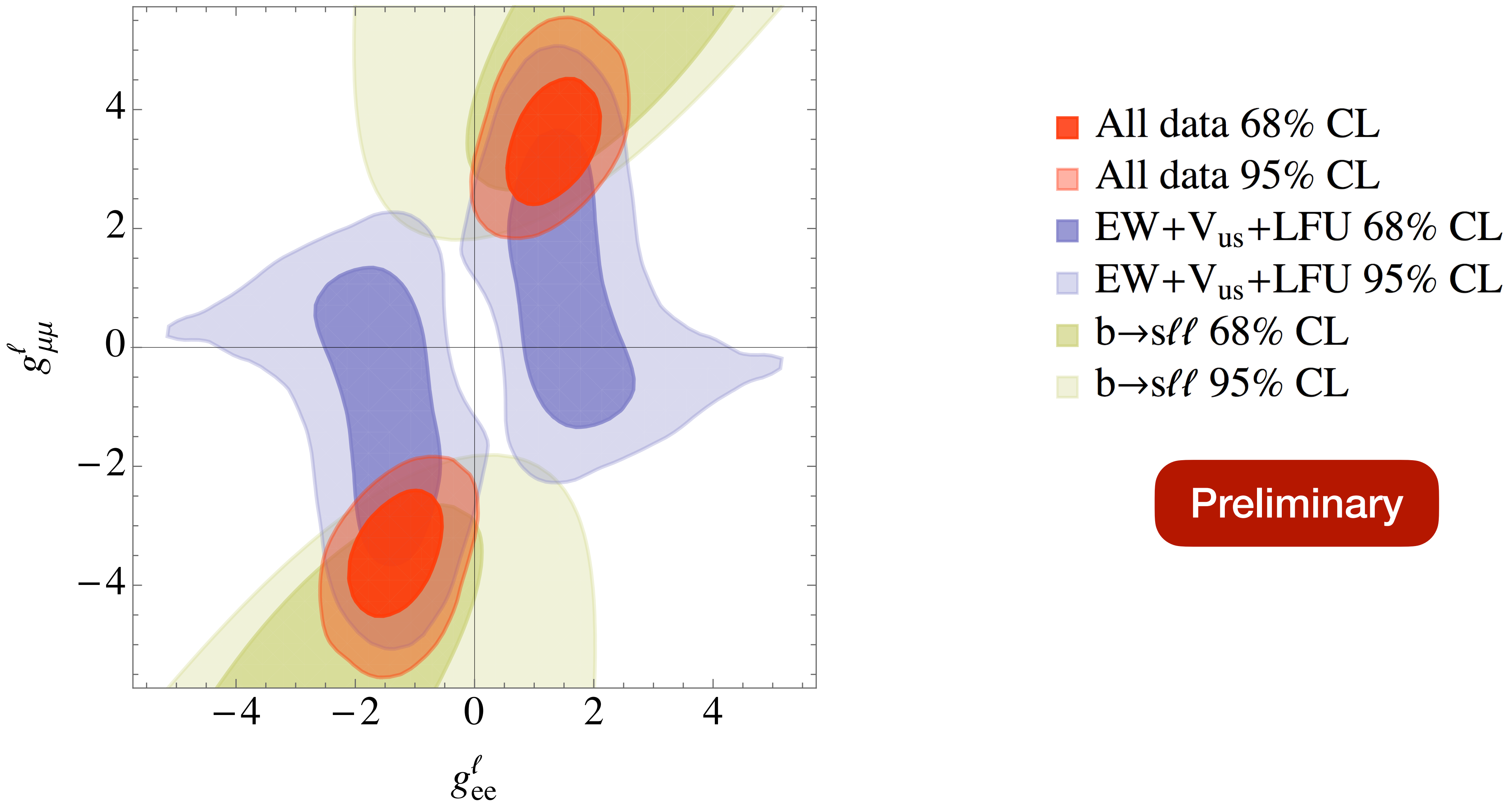
$$C_{9,j}^{NP} = -C_{10,j}^{NP} = -\frac{16\pi^2}{e^2}\frac{g_{23}^d g_{jj}^\ell}{16\sqrt{2}G_F M_X^2 V_{tb}V_{ts}^*}$$



Pull SM = 5.6 σ

Global Fit

$IC_{SM} \simeq 167.72$ $IC_{NP} \simeq 102.25$



Preliminary

Conclusions (I)

- There is a tension in the determination of V_{us} from different processes
- It can be seen as an evidence of LFUV completing an already interesting picture
- We tried to solve the tension modifying the couplings of neutrinos with gauge bosons
- The global fit to EW, LFU and V_{us} prefers LFUV NP at more than 99% C.L.

University of Zurich

Conclusions (II)

- We tried to solve the anomaly with a different tree-level effects, and the Vector Triplet model turned to be a good candidate

- With this simplified model, we are able to explain $b \to s\ell\ell$ and CAA simultaneously

This results are of notable importance for research at PSI, since they emphasise the need for precise tests of LFU

Example

$$R^{\pi,\mathrm{exp}}_{\mu/e} = 1.0010 \pm 0.0009$$

$$R^{\pi,\mathrm{SM}}_{\mu/e} = 1 \to R^{\pi}_{\mu/e} = \boxed{1.00173 \pm 0.00043}$$

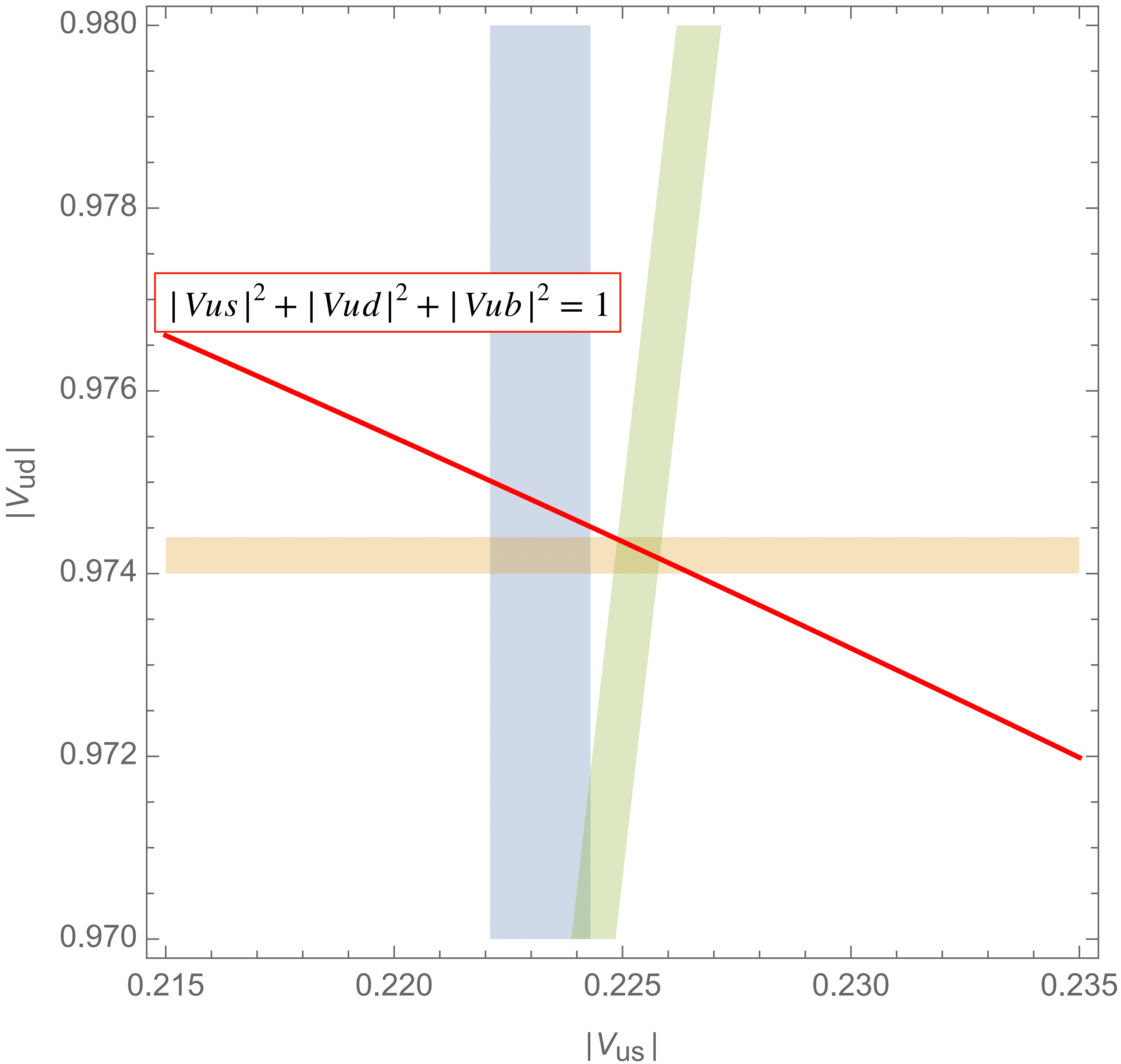
PREDICTION WITH MODIFIED NEUTRINO COUPLINGS

Looking forward to see PEN **results!!!**

PAUL SCHERRER INSTITUT PSI

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

$$|V_{ud}|_{CMS} = 0.97389(18)$$

$$|V_{ud}|_{SGPR} = 0.97370(14)$$

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)

dim = 6

There is 1 Operator which modifies only neutrino couplings :

$$\bar{L}_i \gamma_\mu \tau^I L_j H^\dagger i D_I^\mu H \quad \text{with} \quad \tau^I = (1\,, -\sigma_1\,, -\sigma_2\,, -\sigma_3)$$

$$\frac{-ig_2}{\sqrt{2}} \bar{\ell}_i \gamma^\mu P_L \nu_j W_\mu \Rightarrow \frac{-ig_2}{\sqrt{2}} \bar{\ell}_i \gamma^\mu P_L \nu_j W_\mu \left(\delta_{ij} + \frac{1}{2} \varepsilon_{ij} \right)$$

$$\frac{-ig_2}{2c_W} \bar{\nu}_i \gamma^\mu P_L \nu_j Z_\mu \Rightarrow \frac{-ig_2}{2c_W} \bar{\nu}_i \gamma^\mu P_L \nu_j Z_\mu \left(\delta_{ij} + \varepsilon_{ij} \right)$$

Parameters of Fit I

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-I posterior	NP-II posterior
$V_{us}^{\mathcal{L}}$	0.225 ± 0.010	0.2248 ± 0.0004	0.2248 ± 0.0004
ε_{ee}	0.00 ± 0.05	-0.0018 ± 0.0006	-0.0022 ± 0.0007
$\varepsilon_{\mu\mu}$	0.00 ± 0.05	0.0008 ± 0.0004	0.0012 ± 0.0003
$\varepsilon_{\tau\tau}$	0.00 ± 0.05	-0.0002 ± 0.0020	-0.0003 ± 0.0020

EW Observables of Fit I

Observable	Ref.	Measurement	SM Posterior	NP-I posterior	NP-II posterior	Pull I	Pull II
M_W [GeV]	[3]	80.379(12)	80.363(4)	80.371(6)	80.370(6)	0.67	0.59
Γ_W [GeV]	[3]	2.085(42)	2.089(1)	2.090(1)	2.090(1)	-0.02	-0.02
BR($W \to$ had)	[3]	0.6741(27)	0.6749(1)	0.6749(2)	0.6749(1)	0	0
$\sin^2\theta_{\rm eff}^{\rm lept}(Q_{\rm FB}^{\rm had})$	[3]	0.2324(12)	0.2316(4)	0.2315(1)	0.2315(1)	-0.1	-0.1
$\sin^2\theta_{\rm eff(Tev)}^{\rm lept}$	[3]	0.23148(33)	0.2316(4)	0.2315(1)	0.2315(1)	0.17	0.17
$\sin^2\theta_{\rm eff(LHC)}^{\rm lept}$	[3]	0.23104(49)	0.2316(4)	0.2315(1)	0.2315(1)	-0.03	-0.03
$P_\tau^{\rm pol}$	[7]	0.1465(33)	0.1461(3)	0.1474(8)	0.1472(8)	-0.14	-0.09
A_ℓ	[7]	0.1513(21)	0.1461(3)	0.1474(8)	0.1472(8)	0.72	0.60
Γ_Z [GeV]	[7]	2.4952(23)	2.4947(6)	2.496(1)	2.496(1)	-0.11	-0.11
σ_h^0 [nb]	[7]	41.541(37)	41.485(6)	41.495(24)	41.493(24)	0.47	0.42
R_ℓ^0	[7]	20.767(35)	20.747(7)	20.749(7)	20.749(7)	0.06	0.06
$A_{\rm FB}^{0,\ell}$	[7]	0.0171(10)	0.0160(7)	0.0163(2)	0.0163(2)	0.12	0.12
R_b^0	[7]	0.21629(66)	0.21582(1)	0.21582(1)	0.21582(1)	0	0
R_c^0	[7]	0.1721(30)	0.17219(2)	0.17220(2)	0.17220(2)	0	0
$A_{\rm FB}^{0,b}$	[7]	0.0992(16)	0.1024(2)	0.1033(6)	0.1032(6)	-0.41	-0.36
$A_{\rm FB}^{0,c}$	[7]	0.0707(35)	0.0731(2)	0.0738(4)	0.0738(4)	-0.20	-0.20
A_b	[7]	0.923(20)	0.93456(2)	0.9347(1)	0.9347(1)	-0.01	-0.01
A_c	[7]	0.670(27)	0.6675(1)	0.6680(4)	0.6680(3)	0	0

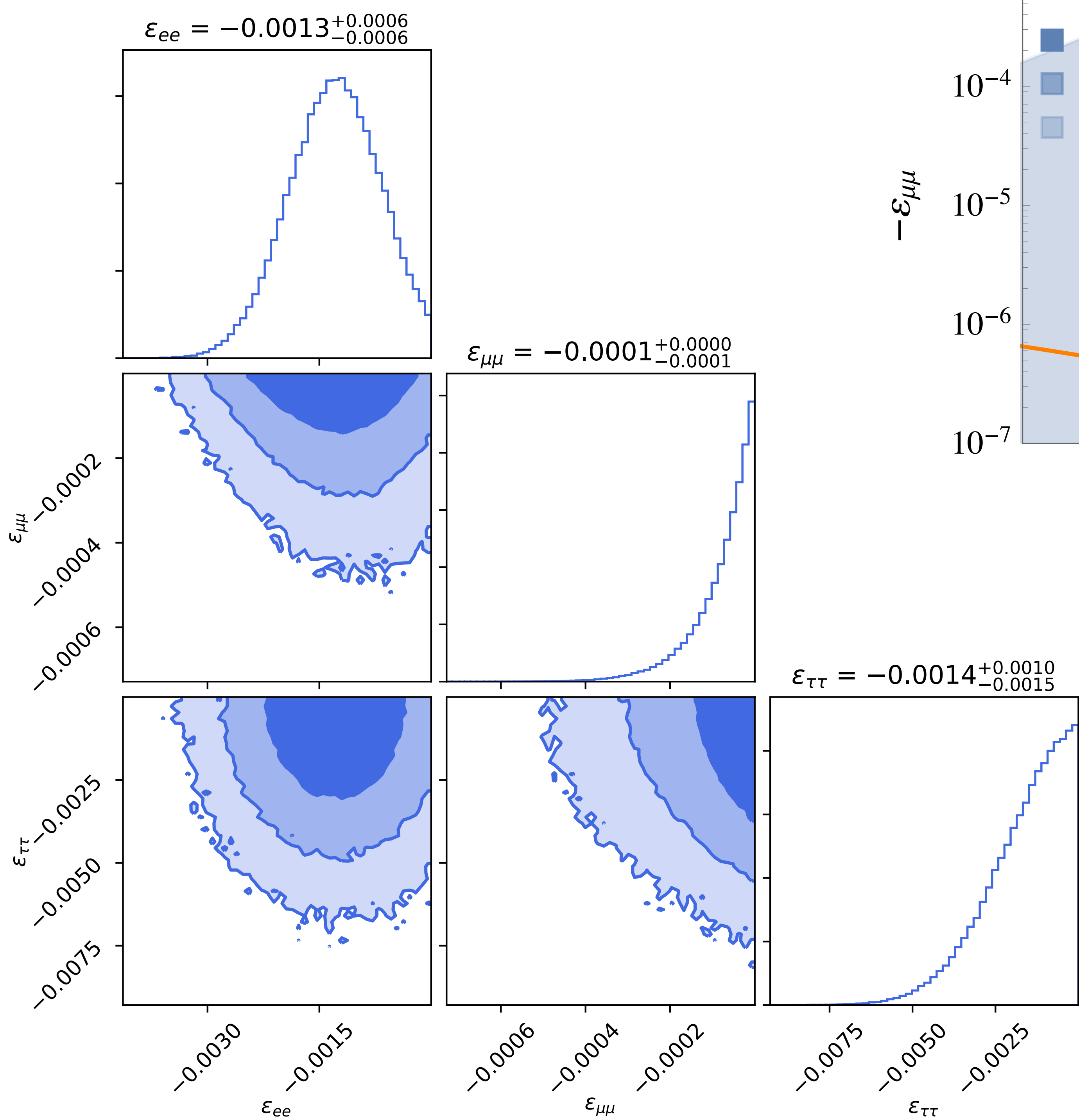
$$P(O_i) = \left|\frac{O_i^{\rm exp} - O_i^{\rm SM}}{\sqrt{(\sigma_i^{\rm exp})^2 + (\sigma_i^{\rm SM})^2}}\right| - \left|\frac{O_i^{\rm exp} - O_i^{\rm NP}}{\sqrt{(\sigma_i^{\rm exp})^2 + (\sigma_i^{\rm NP})^2}}\right|$$

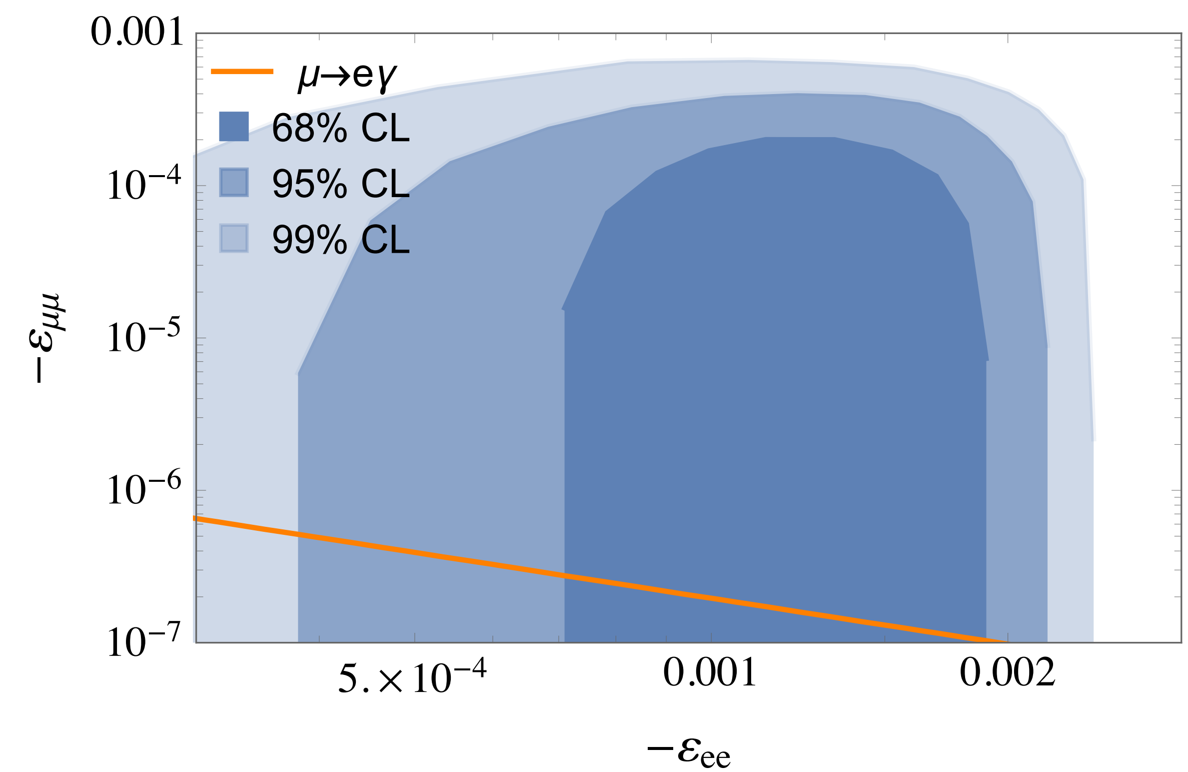
LFU & V_{us} Observables of Fit I

Observable	Ref.	Measurement	SM Posterior	NP-I posterior	NP-II posterior	Pull I	Pull II
$\frac{K\to\mu\nu}{K\to e\nu}$	[1, 14–16]	0.9978 ± 0.0020	1	1.00137 ± 0.00046	1.00173 ± 0.00043	-0.63	-0.82
$\frac{\pi\to\mu\nu}{\pi\to e\nu}$	[2, 3, 16–19]	1.0010 ± 0.0009	1	1.00137 ± 0.00046	1.00173 ± 0.00043	0.75	0.38
$\frac{\tau\to\mu\nu\bar{\nu}}{\tau\to e\nu\bar{\nu}}$	[3, 4]	1.0018 ± 0.0014	1	1.00137 ± 0.00046	1.00173 ± 0.00043	0.99	1.24
$\frac{K\to\pi\mu\bar{\nu}}{K\to\pi e\bar{\nu}}$	[1, 20, 21]	1.0010 ± 0.0025	1	1.00137 ± 0.00046	1.00173 ± 0.00043	0.25	0.11
$\frac{W\to\mu\bar{\nu}}{W\to e\bar{\nu}}$	[1, 5]	0.996 ± 0.010	1	1.00137 ± 0.00046	1.00173 ± 0.00043	-0.14	-0.17
$\frac{B\to D^{(*)}\mu\nu}{B\to D^{(*)}e\nu}$	[6]	0.989 ± 0.012	1	1.00137 ± 0.00046	1.00173 ± 0.00043	-0.11	-0.14
$\frac{\tau\to e\nu\bar{\nu}}{\mu\to e\bar{\nu}\nu}$	[3, 4]	1.0010 ± 0.0014	1	0.9997 ± 0.0010	0.9995 ± 0.0010	-0.04	-0.15
$\frac{\tau\to\pi\nu}{\pi\to\mu\bar{\nu}}$	[4]	0.9961 ± 0.0027	1	0.9997 ± 0.0010	0.9995 ± 0.0010	0.20	0.26
$\frac{\tau\to K\nu}{K\to\mu\bar{\nu}}$	[4]	0.9860 ± 0.0070	1	0.9997 ± 0.0010	0.9995 ± 0.0010	0.06	0.09
$\frac{W\to\tau\bar{\nu}}{W\to\mu\bar{\nu}}$	[1, 5]	1.034 ± 0.013	1	0.9997 ± 0.0010	0.9995 ± 0.0010	-0.02	-0.03
$\frac{\tau\to\mu\nu\bar{\nu}}{\mu\to e\nu\bar{\nu}}$	[3, 4]	1.0029 ± 0.0014	1	1.0011 ± 0.0011	1.0013 ± 0.0011	1.06	1.17
$\frac{W\to\tau\bar{\nu}}{W\to e\bar{\nu}}$	[1, 5]	1.031 ± 0.013	1	1.0011 ± 0.0011	1.0013 ± 0.0011	0.10	0.11
$\lvert V_{us}^{K_{\mu 3}}\rvert$	[3, 22]	0.2234 ± 0.0008	0.2257(3)	0.22509 ± 0.00040	0.22516 ± 0.00040	0.81	0.74
$\lvert V_{us}/V_{ud}\rvert^{K/\pi}$	[22, 23]	0.2313 ± 0.0005	0.2317(4)	0.23078 ± 0.00044	0.23082 ± 0.00044	-0.16	-0.10
$\lvert V_{us}^{\tau}\rvert_{\text{incl.}}$	[24, 25]	0.2195 ± 0.0019	0.2257(3)	0.22487 ± 0.00041	0.22491 ± 0.00041	0.48	0.45
$\lvert V_{ud}^{\beta}\rvert_{\text{CMS}}$	[24, 25]	0.97389 ± 0.00018	0.974185(79)	0.97400 ± 0.00017	-	0.56	-
$\lvert V_{ud}^{\beta}\rvert_{\text{SGPR}}$	[24, 26]	0.97370 ± 0.00014	0.974185(79)	-	0.97379 ± 0.00013	-	2.57

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

Right-handed Neutrinos Fit





Lepton Radiative Decays Bounds

$$|\varepsilon_{e\mu}| \leq 1.4 \times 10^{-5}$$
$$|\varepsilon_{\mu\tau}| \leq 9.4 \times 10^{-3}$$
$$|\varepsilon_{e\tau}| \leq 1.1 \times 10^{-2}$$

$$|\varepsilon_{e\mu}| = \sqrt{|\varepsilon_{ee}||\varepsilon_{\mu\mu}|}$$

Mixing for the Vector Triplet Model

After EWSB

$$M_0^2 = \begin{pmatrix} M^2_{Z^{(0)}} & \frac{x}{c_W} \\ \frac{x^*}{c_W} & M_X^2 \end{pmatrix} \qquad M_\pm^2 = \begin{pmatrix} M^2_{W^{(0)}} & x \\ x^* & M_X^2 \end{pmatrix} \qquad x = M_{W^{(0)}} \frac{g_X^{D\phi} v}{2}$$

$$\begin{pmatrix} W'_\pm \\ W_\pm \end{pmatrix} = \begin{pmatrix} X_\pm \cos\alpha_{WW'} - W_\pm^{(0)} \sin\alpha_{WW'} \\ X_\pm \sin\alpha_{WW'} + W_\pm^{(0)} \cos\alpha_{WW'} \end{pmatrix}$$

$$\sin\alpha_{WW'} \approx \frac{x}{M_X^2} \qquad \sin\alpha_{ZZ'} \approx \frac{x}{M_X^2 x_W}$$

LHC bounds for the Vector Triplet Model

2-quarks-2-leptons

$$-\frac{4\pi}{(24\text{TeV}^2)} \leq \frac{g^\ell_{11} g^q}{4M_{Z'}} \leq \frac{4\pi}{(37\text{TeV}^2)}$$

$$-\frac{4\pi}{(20\text{TeV}^2)} \leq \frac{g^\ell_{22} g^q}{4M_{Z'}} \leq \frac{4\pi}{(30\text{TeV}^2)}$$

$$-10.5\frac{M^2_{W'}}{(10\text{TeV})^2} \leq g^\ell_{33} g^q \leq 0$$

2-jets

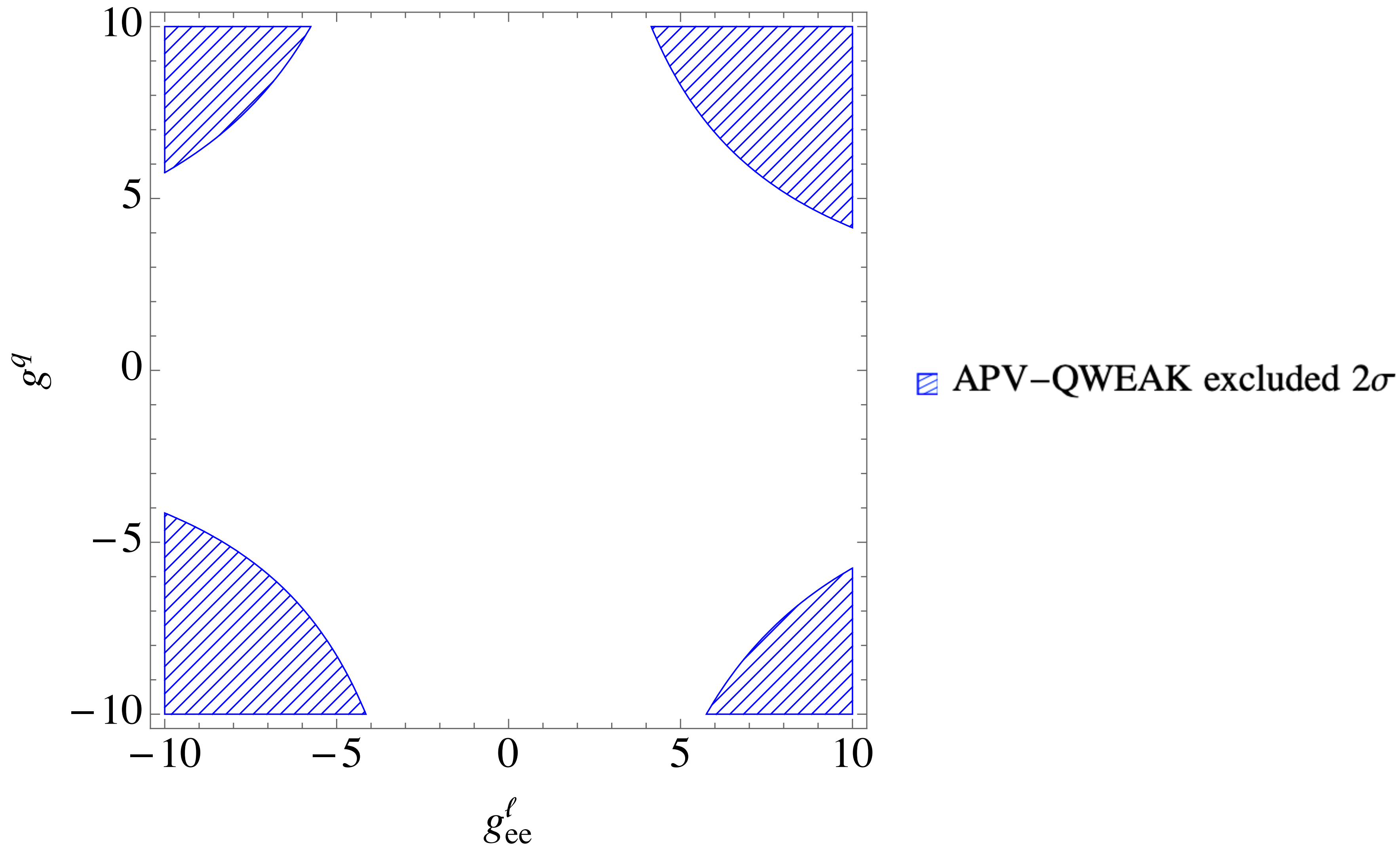
$$|g^q|^2 \leq 15\frac{M^2_{Z'}}{(10\text{TeV})^2}$$

APV & QWEAK bounds for the VT model

QWEAK $-2(2C_{1u} + C_{1d}) = 0.0719 \pm 0.0045$

APV $-2(188C_{1u} + 211C_{1d}) = -72.62 \pm 0.43$

$$C_{1d} = 0.3419 + \frac{\sqrt{2}}{G_F}\frac{g^q g^\ell_{11}}{16M^2_{Z'}} \qquad C_{1u} = -0.1887 - \frac{\sqrt{2}}{G_F}\frac{g^q g^\ell_{11}}{16M^2_{Z'}}$$



Information Criterion

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

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

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