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Vector-like Quarks and Leptons

Portoroz, 11.04.2023

Vector-like Fermions

talk of Gustavo Branco

- Left-handed and right-handed fields have the same quantum numbers (under the SM gauge group)

  ➡ mass not confined to the EW scale

- Special case: Majorana Neutrino
- Can mix with SM fermions via Higgs couplings

  ➡ change W and Z couplings at tree-level

- Motivated by GUTs (E6, E8), Composite/extra-dimensional models (excitations of SM fermions)

Simple consistent extensions of the SM

Vector-like Quarks and Leptons

- Vector-like quarks

	$SU(3)$	$SU(2)_L$	$U(1)_Y$
U	3	1	$2/3$
D	3	1	$-1/3$
Q_1	3	2	$1/6$
Q_5	3	2	$-5/6$
Q_7	3	2	$7/6$
T_1	3	3	$-1/3$
T_2	3	3	$2/3$

$$-\mathrm{L}_{\mathrm{VLL}} = \lambda_N \bar{\ell}\tilde{\phi}N + \lambda_E^i \bar{\ell}\phi E + \lambda_{\Delta_1}\bar{\Delta}_1\phi e + \lambda_{\Delta_3}\bar{\Delta}_3\tilde{\phi}e + \lambda_{\Sigma_0}\tilde{\phi}^\dagger\bar{\Sigma}_0^I\tau^I\ell + \lambda_{\Sigma_1}\phi^\dagger\bar{\Sigma}_1^I\tau^I\ell + \text{ h.c.}$$

- Vector-like leptons

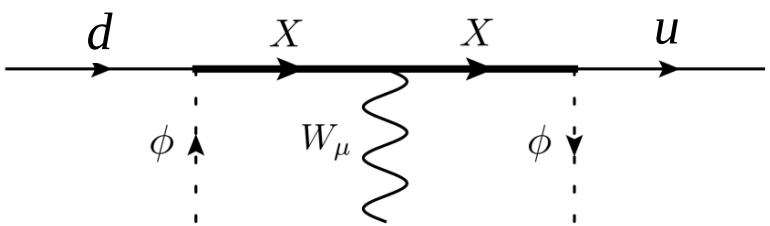
	$SU(3)$	$SU(2)_L$	$U(1)_Y$
N	1	1	0
E	1	1	-1
Δ_1	1	2	$-1/2$
Δ_3	1	2	$-3/2$
Σ_0	1	3	0
Σ_1	1	3	-1

$$-\mathrm{L}_{\mathrm{VLQ}} = \xi^U\bar{U}\tilde{H}^\dagger q + \xi^D\bar{D}H^\dagger q + \xi^{u_1}\bar{Q}_1\tilde{H}u + \xi^{d_1}\bar{Q}_1Hd + \xi^{Q_5}\bar{Q}_5\tilde{H}d + \xi^{Q_7}\bar{Q}_7Hu + \frac{1}{2}\xi^{T_1}H^\dagger\tau\cdot\bar{T}_1q + \frac{1}{2}\xi^{T_2}\tilde{H}^\dagger\tau\cdot\bar{T}_2q + \text{ h.c.}$$

7 (6) representations of VLQs (VLLs)

Vector-like Quarks and Leptons

- Vector-like quarks



$$C_{\phi q}^{(1)} = \frac{|\xi^U|^2}{4M_U^2} - \frac{|\xi^D|^2}{4M_D^2} - \frac{3\,|\xi^{T_1}|^2}{16M_{T_1}^2} + \frac{3\,|\xi^{T_2}|^2}{16M_{T_2}^2},$$

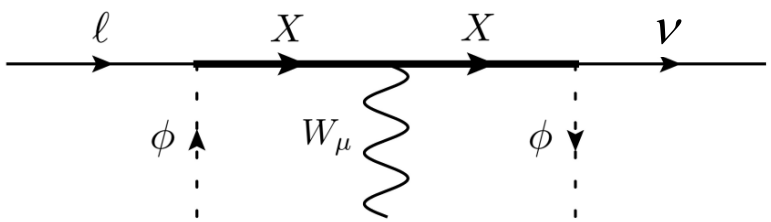
$$C_{\phi q}^{(3)} = -\frac{|\xi^U|^2}{4M_U^2} - \frac{|\xi^D|^2}{4M_D^2} + \frac{|\xi^{T_1}|^2}{16M_{T_1}^2} + \frac{|\xi^{T_2}|^2}{16M_{T_2}^2},$$

$$C_{\phi ud} = \frac{\xi^{d_1}\xi^{u_1 *}}{M_{Q_1}^2},$$

$$C_{\phi u} = -\frac{|\xi^{u_1}|^2}{2M_{Q_1}^2} + \frac{|\xi^{Q_7}|^2}{2M_{Q_7}^2},$$

$$C_{\phi d} = \frac{|\xi^{d_1}|^2}{2M_{Q_1}^2} - \frac{|\xi^{Q_5}|^2}{2M_{Q_5}^2},$$

- Vector-like leptons



$$C_{\phi\ell}^{(1)} = \frac{\lambda_N\lambda_N^\dagger}{4M_N^2} - \frac{\lambda_E\lambda_E^\dagger}{4M_E^2} + \frac{3}{16}\frac{\lambda_{\Sigma_0}^\dagger\lambda_{\Sigma_0}}{M_{\Sigma_0}^2} - \frac{3}{16}\frac{\lambda_{\Sigma_1}^\dagger\lambda_{\Sigma_1}}{M_{\Sigma_1}^2},$$

$$C_{\phi\ell}^{(3)} = -\frac{\lambda_N\lambda_N^*}{4M_N^2} - \frac{\lambda_E\lambda_E^*}{4M_E^2} + \frac{1}{16}\frac{\lambda_{\Sigma_0}^\dagger\lambda_{\Sigma_0}}{M_{\Sigma_0}^2} + \frac{1}{16}\frac{\lambda_{\Sigma_1}^\dagger\lambda_{\Sigma_1}}{M_{\Sigma_1}^2},$$

$$C_{\phi e} = \frac{\lambda_{\Delta_1}^\dagger\lambda_{\Delta_1}}{2M_{\Delta_1}^2} - \frac{\lambda_{\Delta_3}^\dagger\lambda_{\Delta_3}}{2M_{\Delta_3}^2}.$$

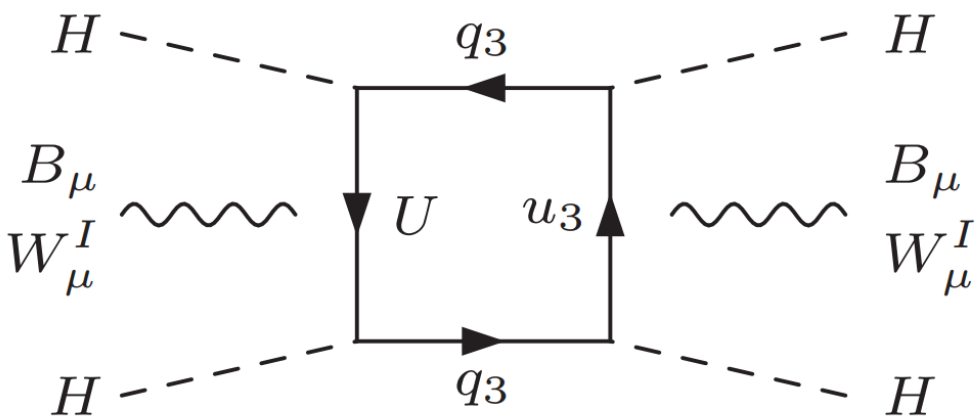
Modified W and Z couplings at tree-level

Relevant Observables

- Z pole
- Muon decay
- Beta decay
- W mass
- Parity violation
- Tests of lepton flavour universality
- Flavour

} **Global EW fit**

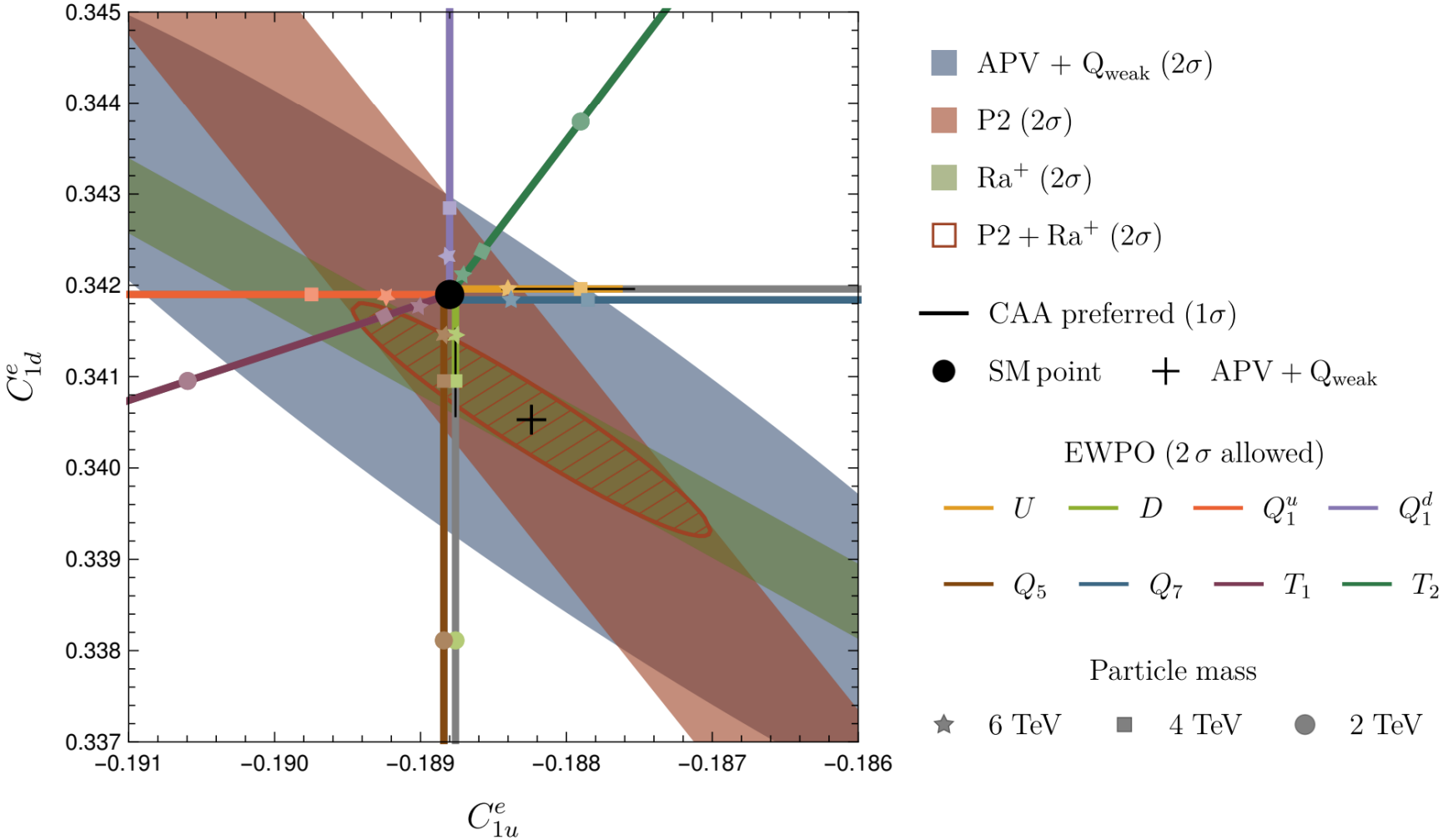
W mass



Interesting and correlated effect in the EW fit

1th generation VLQs

A.C., M. Hoferichter, M. Kirk,
C. Manzari and L. Schnell, 2107.13569



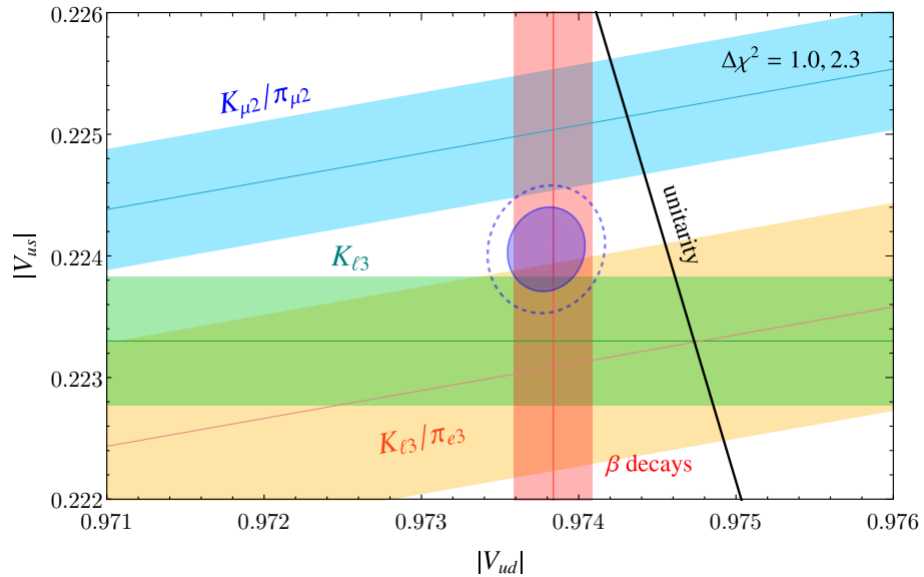
Observable effect in low-energy PV possible

Cabibbo Angle Anomaly (CAA)

- Deficit in first row and first column CKM unitarity

$$\left|V_{ud}^2\right| + \left|V_{us}^2\right| + \left|V_{ub}^2\right| = 0.9985 \pm 0.0005$$
$$\left|V_{ud}^2\right| + \left|V_{cd}^2\right| + \left|V_{td}^2\right| = 0.9970 \pm 0.0018 \qquad (\mathrm{PDG})$$

- Discrepancy between V_{us} from K_{l2} and K_{l3} decays



- Can be explained via
  - NP in beta decays
  - NP in Kaon decays
  - NP in the Fermi constant (muon decay)

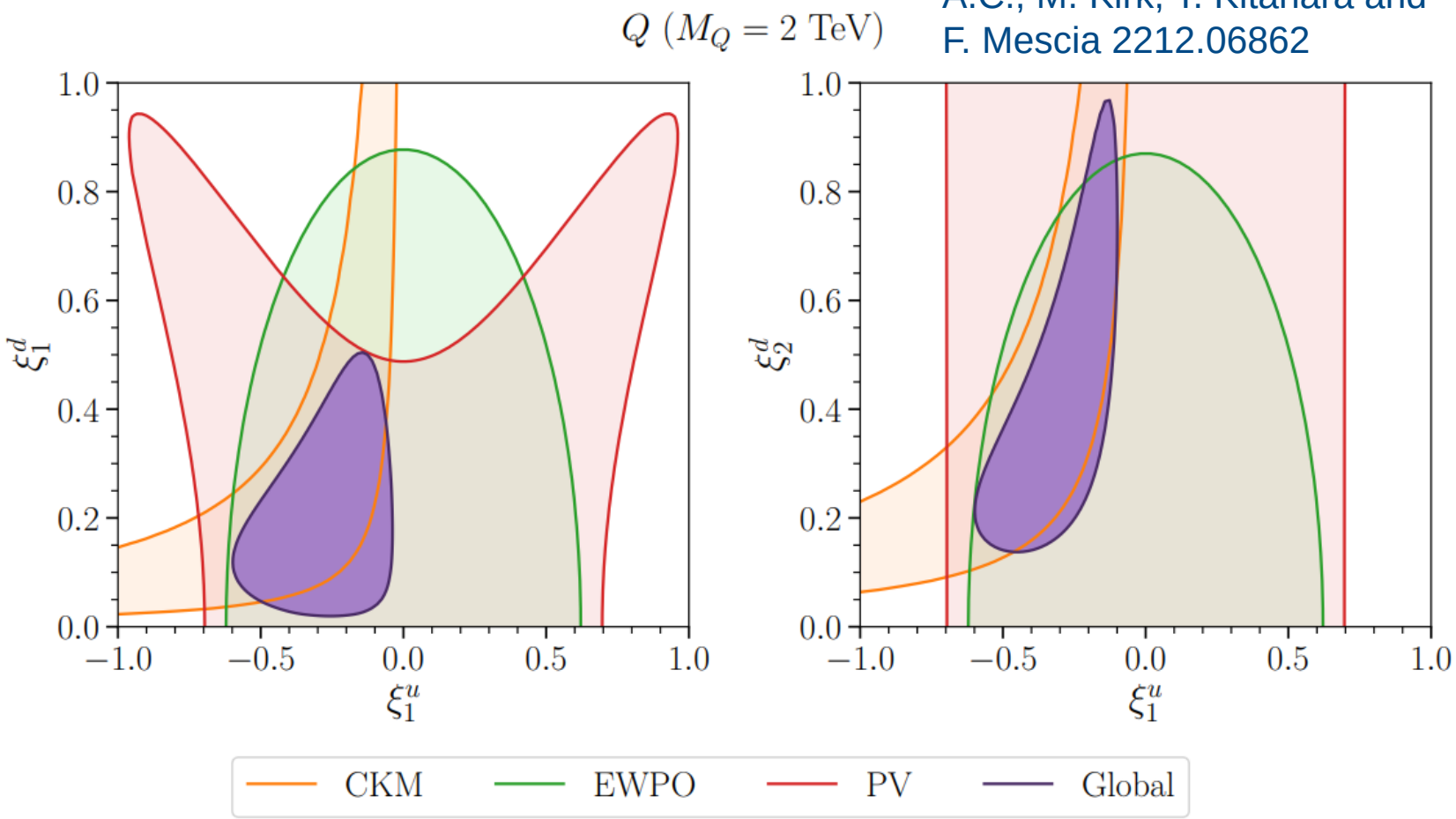
Two O(3σ) tensions, can be explained by VLF

CAA and VLQs

B. Belfatto, Z. Berezhiani 2103.05549

- Modified W coupling

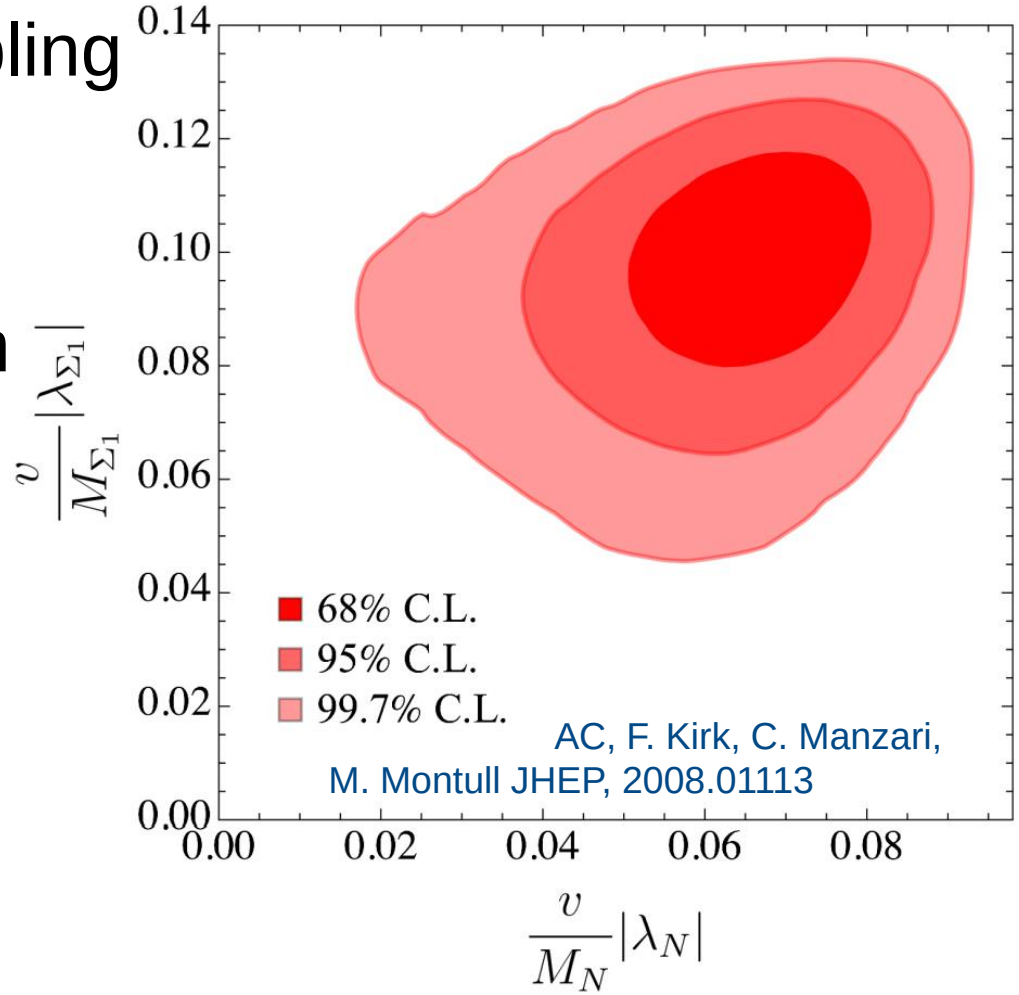
A.C., M. Kirk, T. Kitahara and F. Mescia 2212.06862



SU(2) doublet Q can explain both tensions

CAA and VLLs

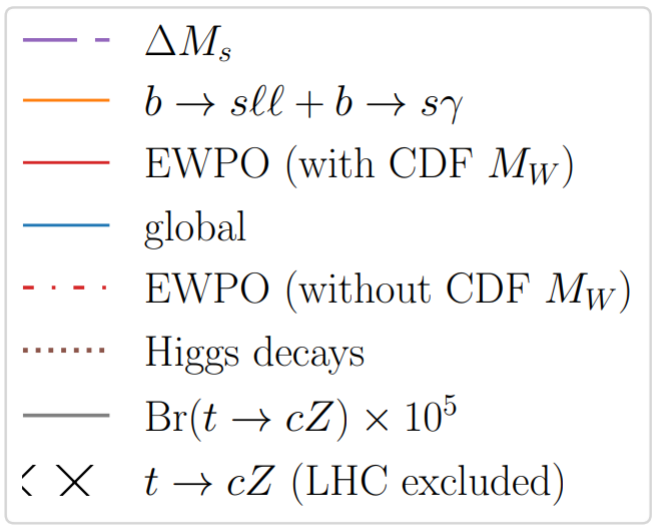
- Modified Wμν coupling changes V_{ud} from beta decays (indirect effect from muon decay)
- Also Zll coupling affected and A_e favours non-zero effect

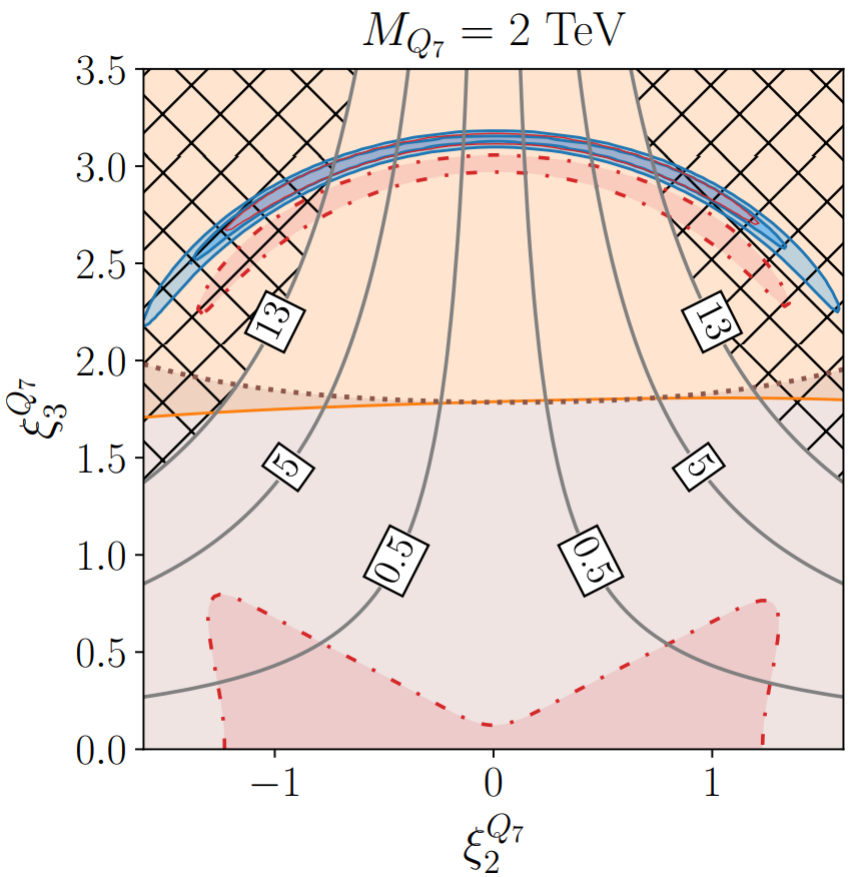


Two VLL representations give very good fit

t→Zc and W mass

- Couplings to right-handed quarks needed avoid flavour bounds





A. Crivellin, M. Kirk, T. Kitahara, F.~Mescia, 2204.05962

VLQ only option for sizable t→cZ

Model for b→sℓℓ, CAA, Z→bb & τ → μνν

- VLQs combied with Z' can explain b→sℓℓ

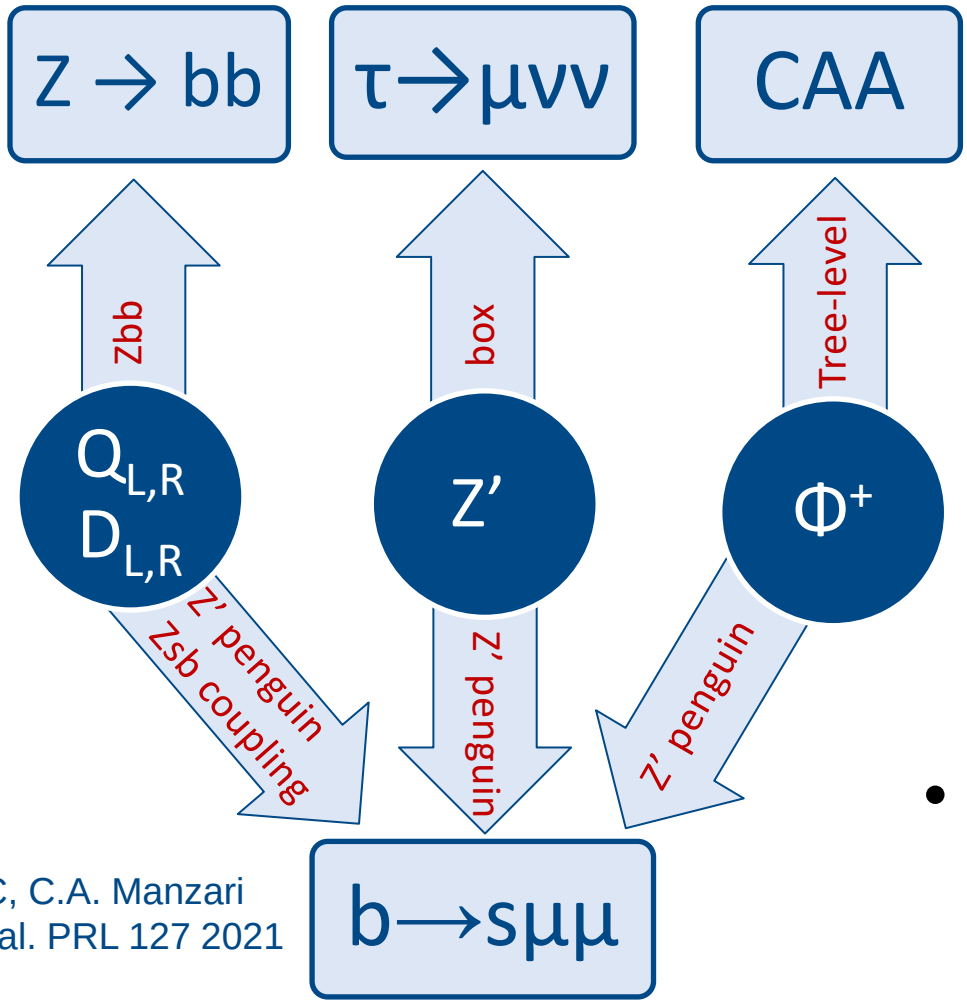
  C. Bobeth, A. Buras, A. Celis, M. Jung, 1609.04783

- $L_e+L_\mu-2L_\tau$ model with vector-like quarks

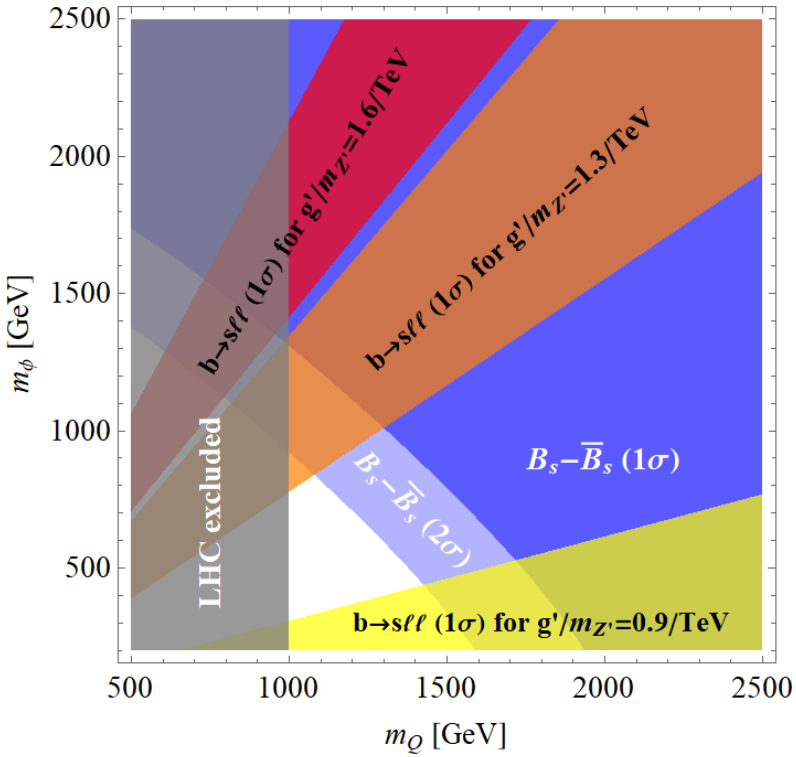
	q_L	d_R	u_R	H	ℓ_L	e_R	Q_L	Q_R	D_L	D_R	ϕ^+	S
$SU(3)_c$	3	3	3	1	1	1	3	3	3	3	1	1
$SU(2)_L$	2	1	1	2	2	1	2	2	1	1	1	1
$U(1)_Y$	$\frac{1}{6}$	$\frac{-1}{3}$	$\frac{2}{3}$	$\frac{1}{2}$	$\frac{-1}{2}$	-1	$\frac{-5}{6}$	$\frac{-5}{6}$	$\frac{-1}{3}$	$\frac{-1}{3}$	1	0
$U(1)'$	0	0	0	$(1,1,-2)$			0	1	1	0	-1	-1

Lepton flavour universal effect in C9

Model for b→sℓℓ, CAA, Z→bb and τ → μνν



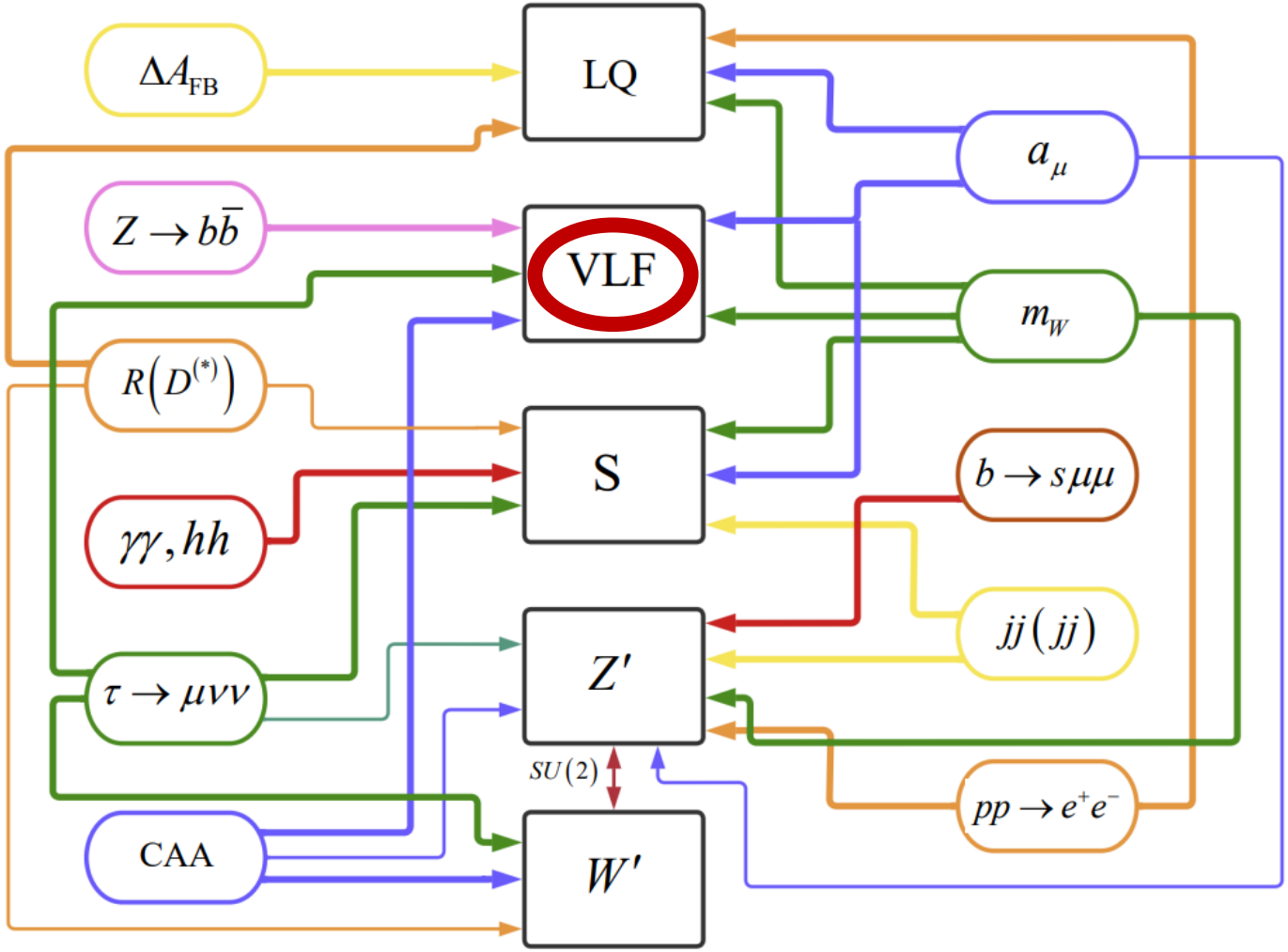
AC, C.A. Manzari et al. PRL 127 2021



- Z' penguin + modified Zsb coupling give very good fit to b→sll data

Simple model provides combined explanation

Conclusions



Vector-like fermions are in interesting option

τ→μνν

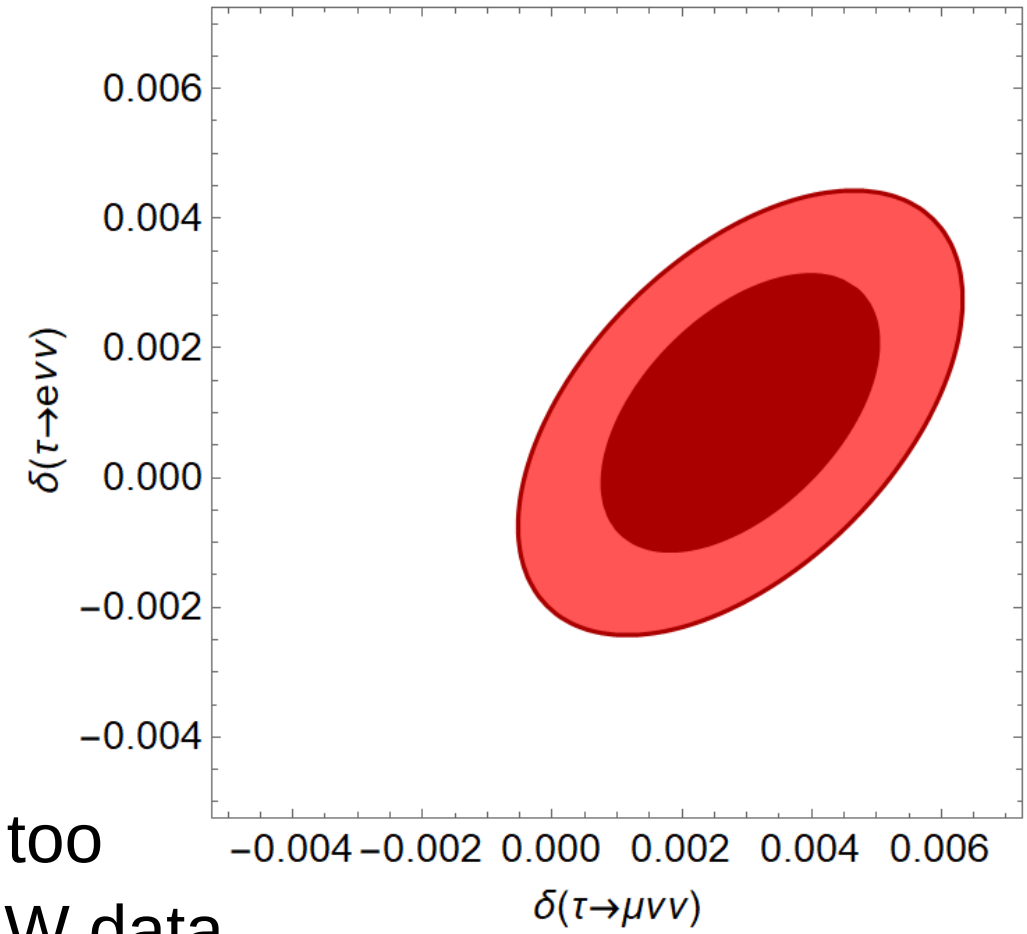
- Ratios of leptonic tau decays

$$\frac{A_{EXP}(\tau \to \mu\nu\bar{\nu})}{A_{SM}(\mu \to e\nu\bar{\nu})} = 1.0029 \pm 0.0014$$

$$\frac{A_{EXP}(\tau \to \mu\nu\bar{\nu})}{A_{SM}(\tau \to e\nu\bar{\nu})} = 1.0018 \pm 0.0014$$

$$\frac{A_{EXP}(\tau \to e\nu\bar{\nu})}{A_{SM}(\mu \to e\nu\bar{\nu})} = 1.0010 \pm 0.0014$$

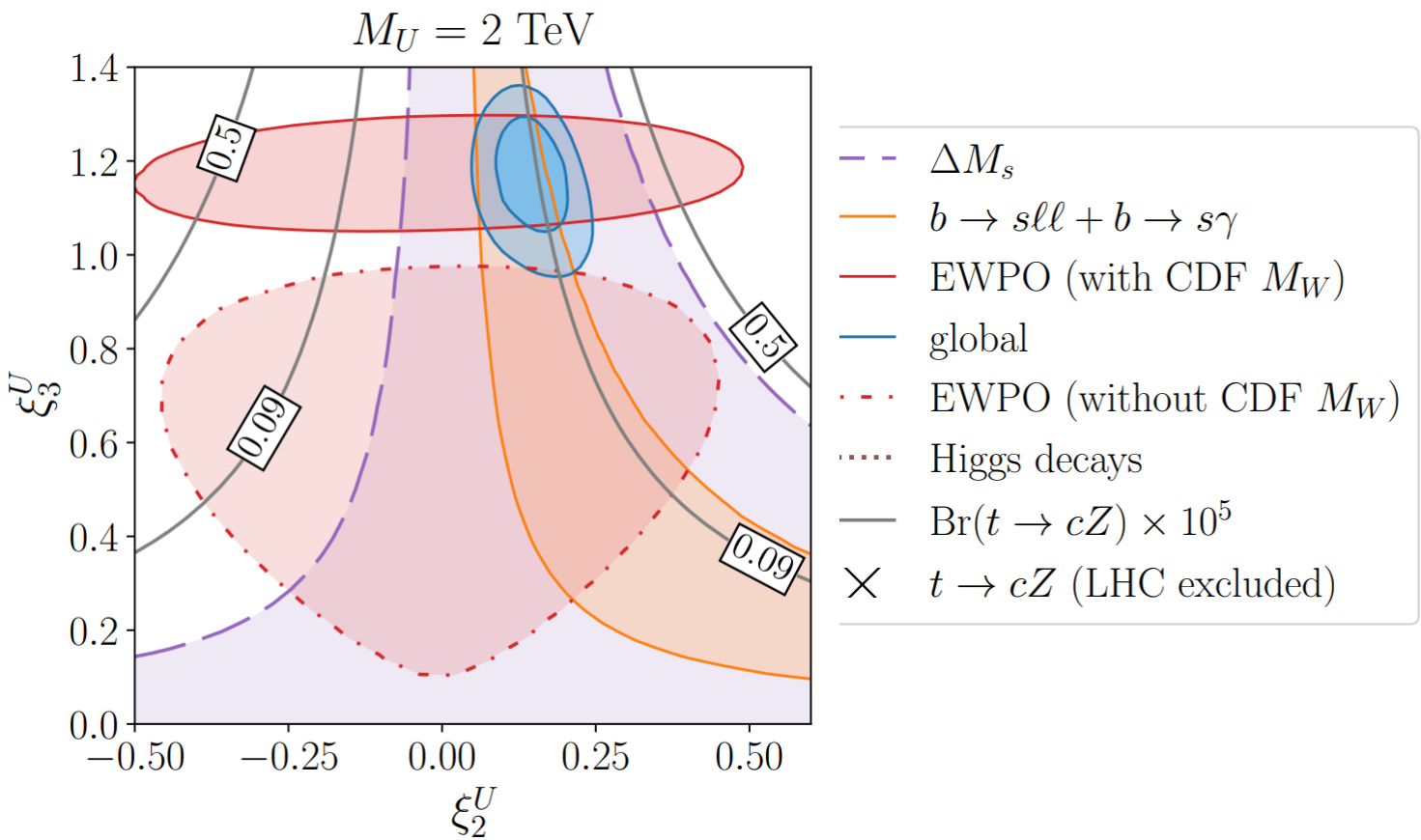
$$\rho = \begin{pmatrix} 1.00 & 0.49 & 0.51 \\ 0.49 & 1.00 & -0.49 \\ 0.51 & -0.49 & 1.00 \end{pmatrix}$$



- NP in muon decay too constrained from EW data

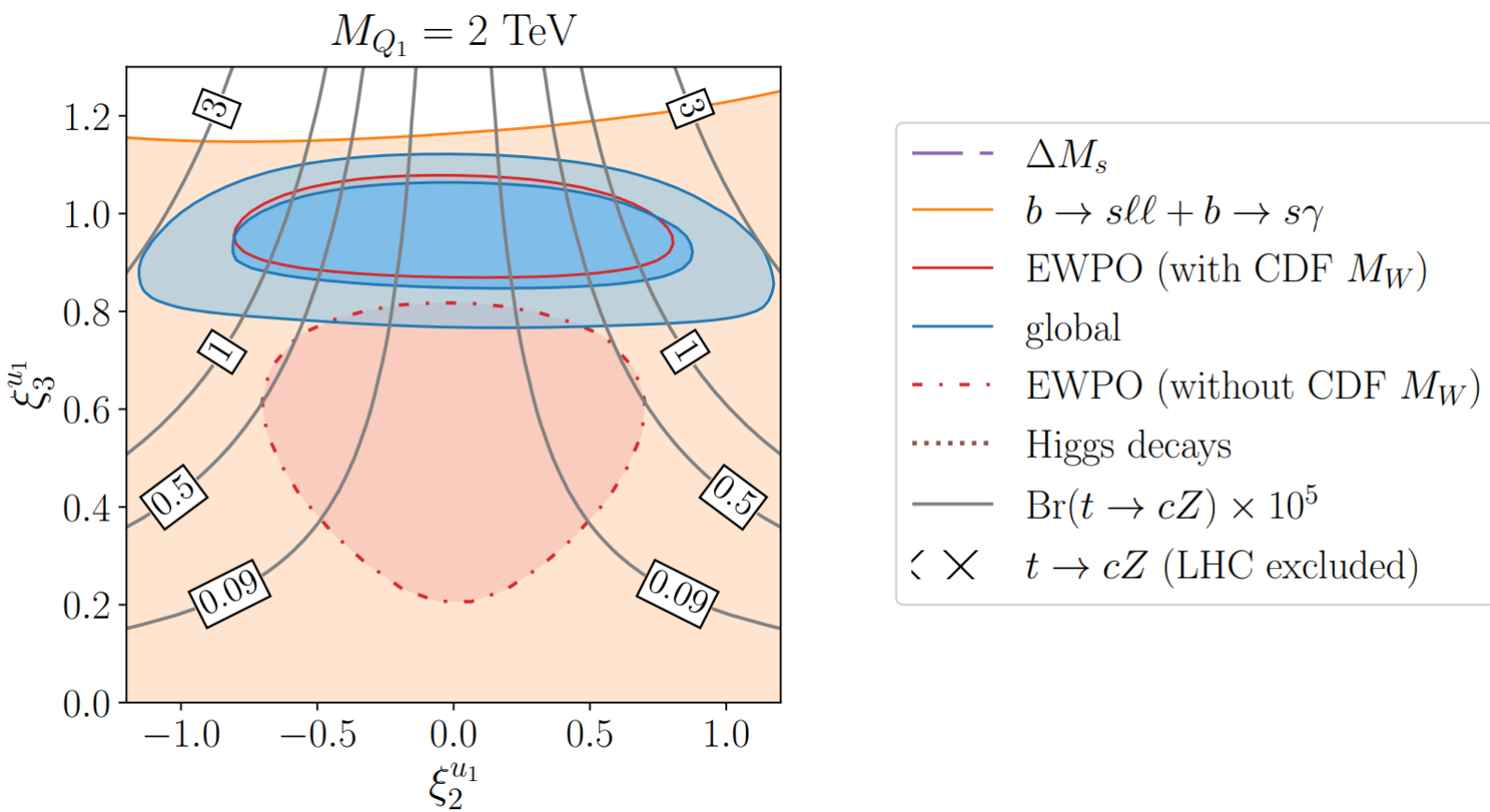
≈2σ hint for LFUV in tau decays

t→Zc and W mass



VLQ only option for large t→cZ

t→Zc and W mass



VLQ only option for large t→cZ