PAUL SCHERRER INSTITUT

Universität Zürich[UZH]

Andreas Crivellin

Theory Group of the Laboratory for Particle Physics, PSI & University of Zurich

Theoretical Motivations for a large Muon EDM

Based on: AC, and M. Hoferichter and P. Schmidt-Wellenburg: PRD.98.113002, arXiv:1807.11484

Outline

- Introduction: Searching for NP with flavour observables
- Experimental situation: Lepton Flavour Universality Violation
- Anomalous magnetic moments
  - a_μ
  - a_e
- Combined explanations
- A large muon EDM
- Conclusions

Physics Beyond the Standard Model

PAUL SCHERRER INSTITUT PSI

- Dark Matter existence established at cosmological scales
  - New weakly interacting particles
- Neutrinos not exactly massless
  - Right-handed (sterile) neutrinos
- Matter anti-matter asymmetry
  - Additional CP violating interactions

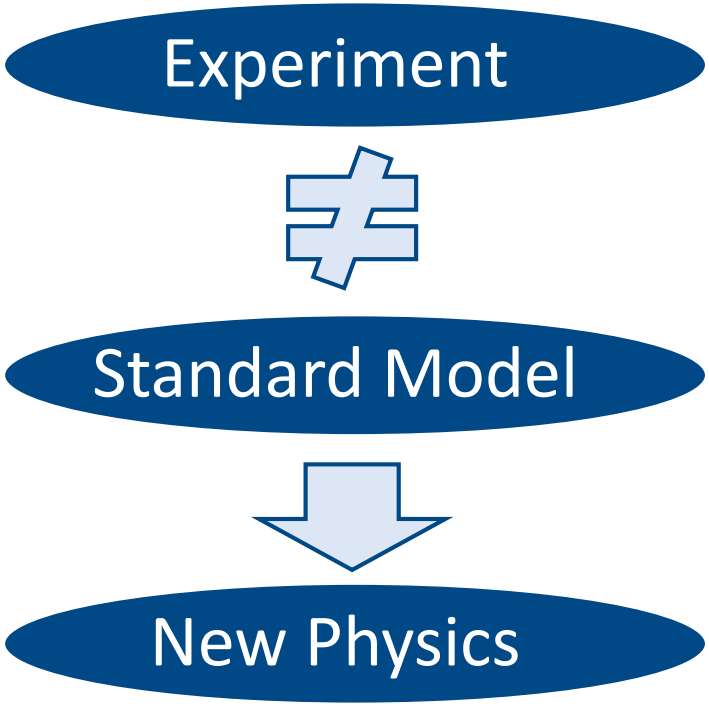
New particles and interactions exist!

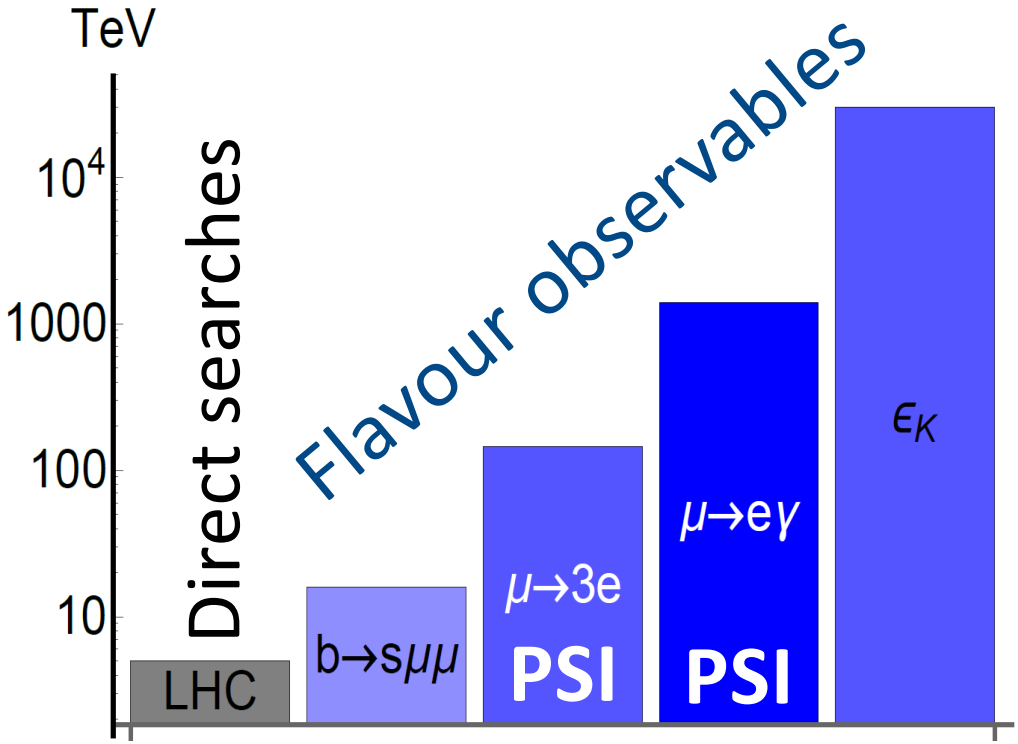
The SM must be extended!
What is the underlying fundamental theory?

Finding New Physics with Flavour

Universität Zürich[UZH]

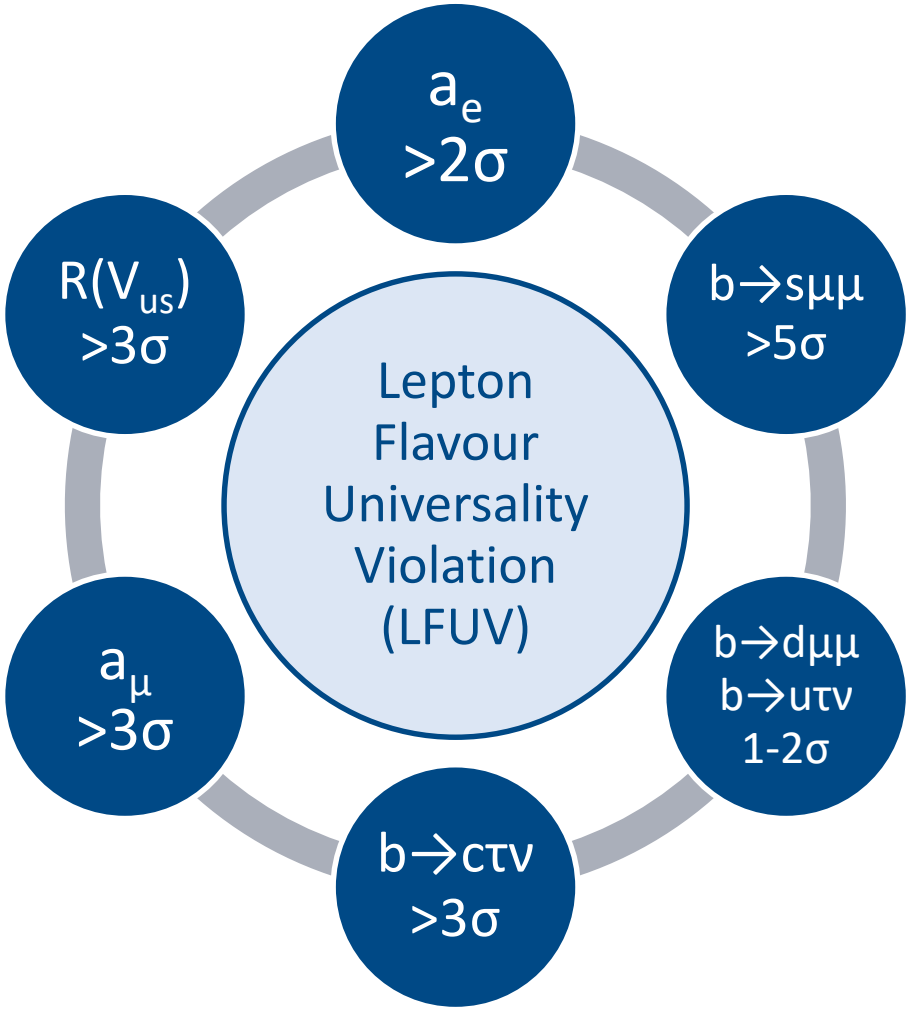
- At colliders one produces many (up to 10^{14}) heavy quarks or leptons and measures their decays into light flavours

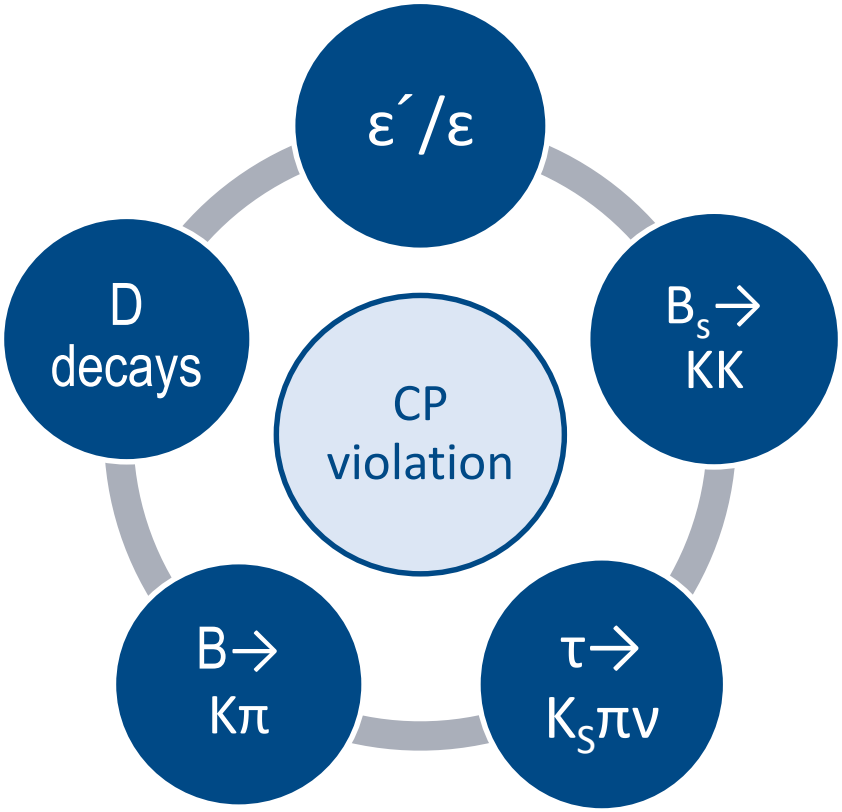




Flavour observables are sensitive to higher energy scales than collider searches

Hints for New Physics





CP + LFUV → muon EDM?

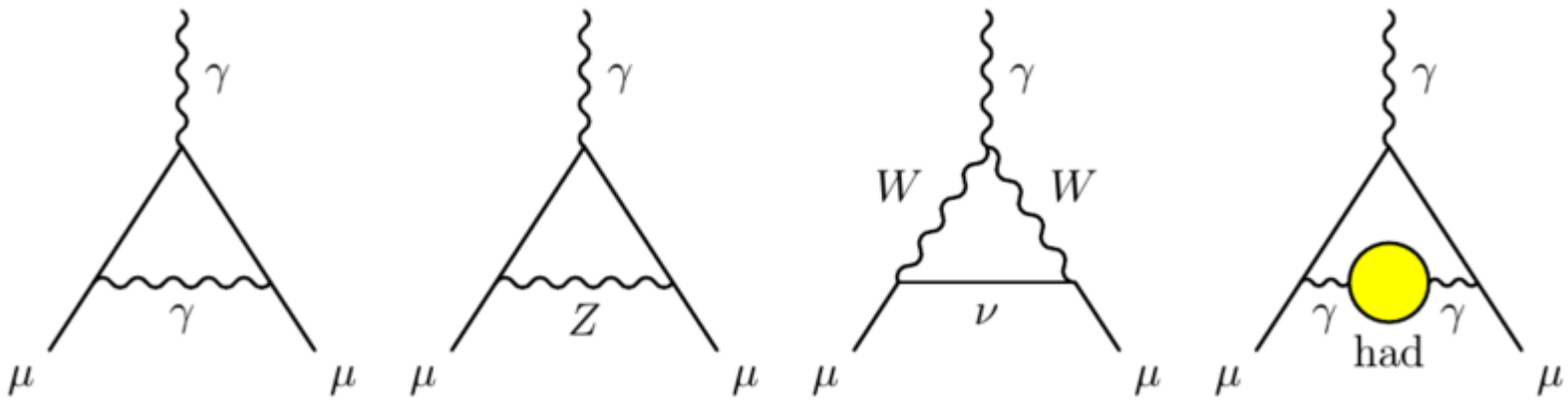
Muon Anomalous Magnetic Momen

Universität Zürich[UZH]

- Single measurement from BNL
- Theory prediction sound but challenging because of hadronic effects.

$$\Delta a_\mu = (236 \pm 87) \times 10^{-11}$$

- Soon new experimental results from Fermilab



3σ deviation (order of SM-EW contribution)

Electron AMM

PAUL SCHERRER INSTITUT

- AMM usually used to determine α
- With *now* best determination of α from Cs atoms

$$a_e^{\mathrm{SM}}\Big|_{\alpha_{\mathrm{Cs}}} = 1{,}159{,}652{,}181.61(23) \times 10^{-12}$$

- Compared to the electron AMM measurement

$$\Delta a_e = a_e^{\mathrm{exp}} - a_e^{\mathrm{SM}} = -0.88(36) \times 10^{-12}$$

- Normalized to the lepton mass

$$-3 \leq \frac{\Delta a_\mu}{m_\mu} \Big/ \frac{\Delta a_e}{m_e} \leq -130 \quad \text{or} \quad -0.006 \leq \frac{\Delta a_\mu}{m_\mu^2} \Big/ \frac{\Delta a_e}{m_e^2} \leq -0.26$$

2.5 σ deviation with opposite sign than a_μ

Dipoles in the EFT

Universität Zürich[UZH]

- Effective Hamiltonian

$$\mathcal{H}_{\text{eff}} = c_R^{\ell_f \ell_i}\, \bar{\ell}_f \sigma_{\mu\nu} P_R \ell_i F^{\mu\nu} + \text{h.c.}$$

- Anomalous magnetic moment

$$a_{\ell_i} = -\frac{4 m_{\ell_i}}{e} \operatorname{Re} c_R^{\ell_i \ell_i}$$

- Electric Dipole moment

$$d_{\ell_i} = -2 \operatorname{Im} c_R^{\ell_i \ell_i}$$

- Radiative Lepton decays

$$\text{Br}[\mu \to e\gamma] = \frac{m_\mu^3}{4\pi \Gamma_\mu} \left(|c_R^{e\mu}|^2 + |c_R^{\mu e}|^2 \right)$$

Processes intrinsically connected

Explaining the Muon AMM

- Effect of the order of the EW-SM contribution needed

⇒ enhancement necessary

- Light particles
  - Neutral scalars
  - Neutral vector (Z' Dark Photon)
- Chiral enhancement: Chiriality flip does not come from the muon mass but rather from an NP mass inside the loop

Light particles or chiral enhancement

Light particles and the Muon AMM

Universität Zürich[UZH]

- Light particles: m_W^2 / m^2
  - Neutral scalars: Φ
  - Neutral vector (Z' Dark Photon): V

$$c_R^{\mu\mu} = \frac{e}{16\pi^2} m_\mu \left(\left|\Gamma^{\mu L}\right|^2 + \left|\Gamma^{\mu R}\right|^2 \right) \frac{f_{\Phi,V}\left(\frac{M_\Psi^2}{m^2}\right) + Qg\left(\frac{M_\Psi^2}{m^2}\right)}{m^2}$$

$Q = \text{charge of the fermion}$ $\quad f, g = \text{loop functions}$

- Sime sign in muon and electron AMM
- Strong limits from direct searches for dark photons etc..

By construction real, i.e. no EDMs

Chiral enhancement

- Enhancement by the mass of the fermion in the loop

$$c_R^{fi} = \frac{e}{16\pi^2}\Gamma_\Psi^{\mu L*}\Gamma_\Psi^{\mu R} M_\Psi \frac{f\left(\frac{M_\Psi^2}{M^2}\right) + Qg\left(\frac{M_\Psi^2}{M^2}\right)}{M^2}$$

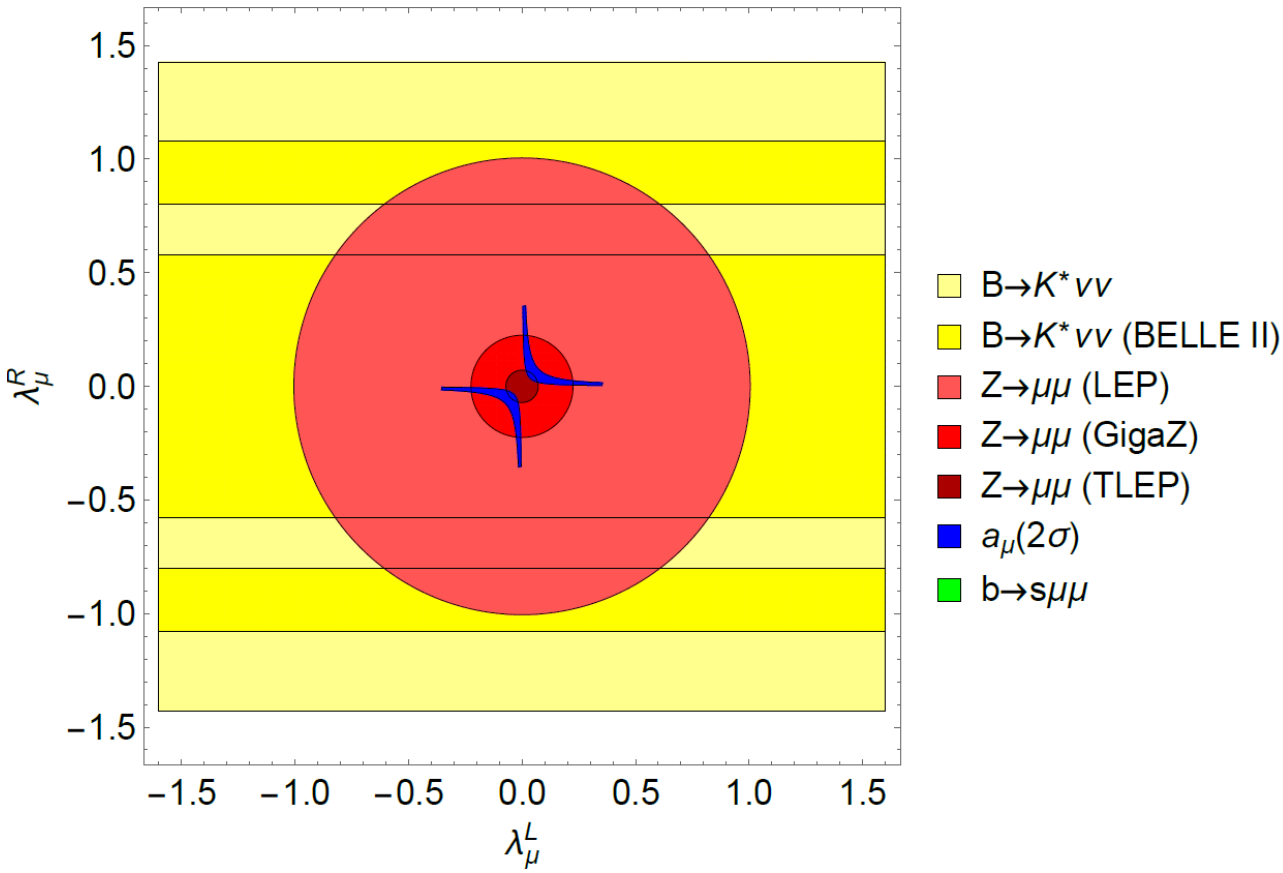
$Q, M_\Psi =$ charge, mass of the fermion $\qquad f, g =$ loop functions

- MSSM: (tan(ß))
- Leptoquarks: m_t/m_μ
- Model with vector like fermions: m_Ψ/m_μ

A priori arbitrary phase

Leptoquarks in a_μ

- Chirally enhanced effects via top-loops



$\lambda_\mu^{L,R}$

Left-, right-handed muons-top coupling

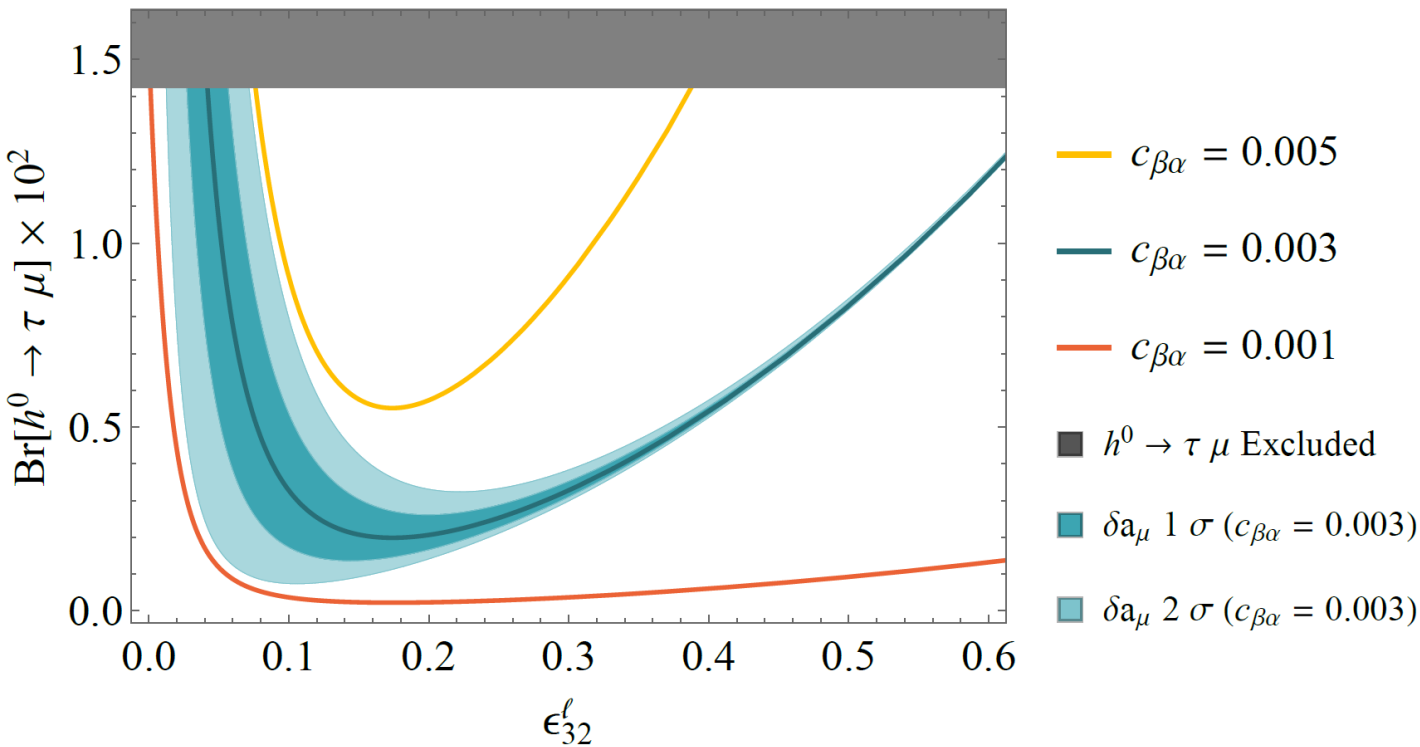
E. Leskow, A.C., G. D'Ambrosio, D. Müller arXiv:1612.06858

Z→μμ at future colliders

2HDMs

- Chirally enhancement of m_μ/m_e

AC, D. Müller, C. Wiegand
arXiv:1903.10440



Unavoidable constraints from h→τμ

Common explanation of a_μ and a_e

Universität Zürich[UZH]

- Opposite sign: ⇒ no single light mediator
- Minimal Flavour Violation:

  $$\Delta a_\mu / \Delta a_e \neq m_\mu^2 / m_e^2$$

  ⇒ generic flavour structure
- Single new particle:

  $$\mathrm{Br}[\mu \to e\gamma] = \frac{\alpha m_\mu^2}{16 m_e \Gamma_\mu} |\Delta a_\mu \Delta a_e| \sim 8 \times 10^{-5}$$

  8 orders of magnitude too large

  ⇒ several new particles

Muon and electron sector must be decoupled

Models for a common explanation

- MSSM
  - Constrained MFV does not work
  - With generic A-terms has problem with vacuum stability
  - With large tan(ß) and flavour violation
- 2HDMs & LQs: Problems with $\mu \to e\gamma$
- Extra dimensions
  - Can only explain the muon or the electron AMM because of $\mu \to e\gamma$

Most popular models do not work

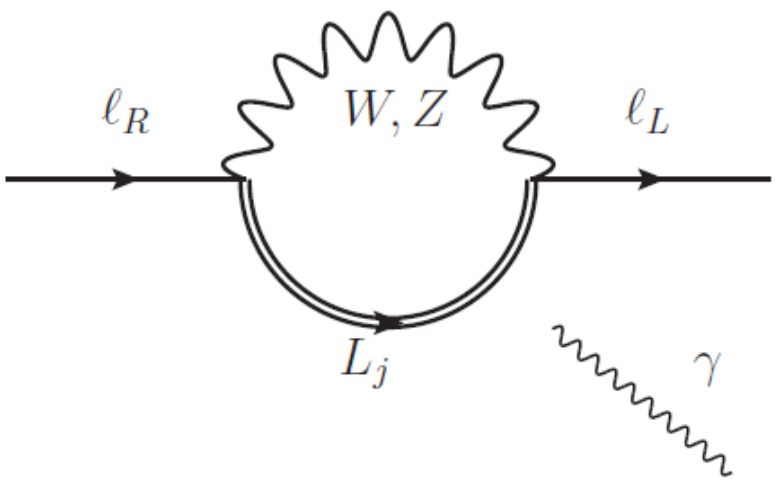
Model with new vector-like leptons

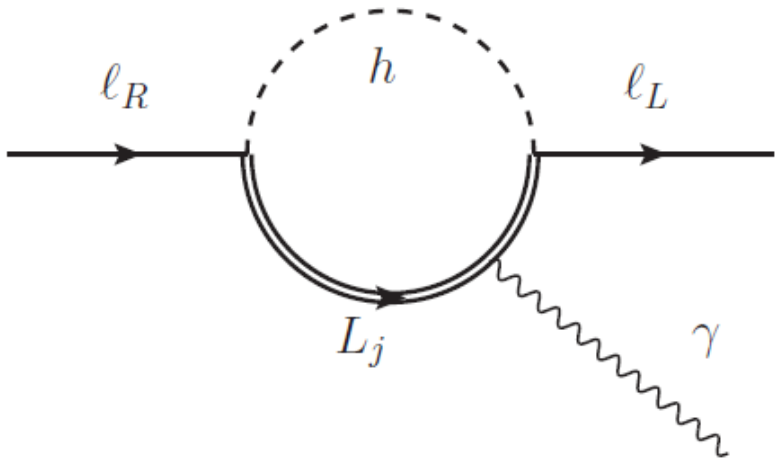
Universität Zürich[UZH]

$$\mathcal{L}_M = -M_L \bar{L}_L L_R - M_E \bar{E}_L E_R + \text{h.c.},$$

$$\mathcal{L}_H = -\kappa_L \bar{L}_L H E_R - \kappa_E \bar{L}_R H E_L$$

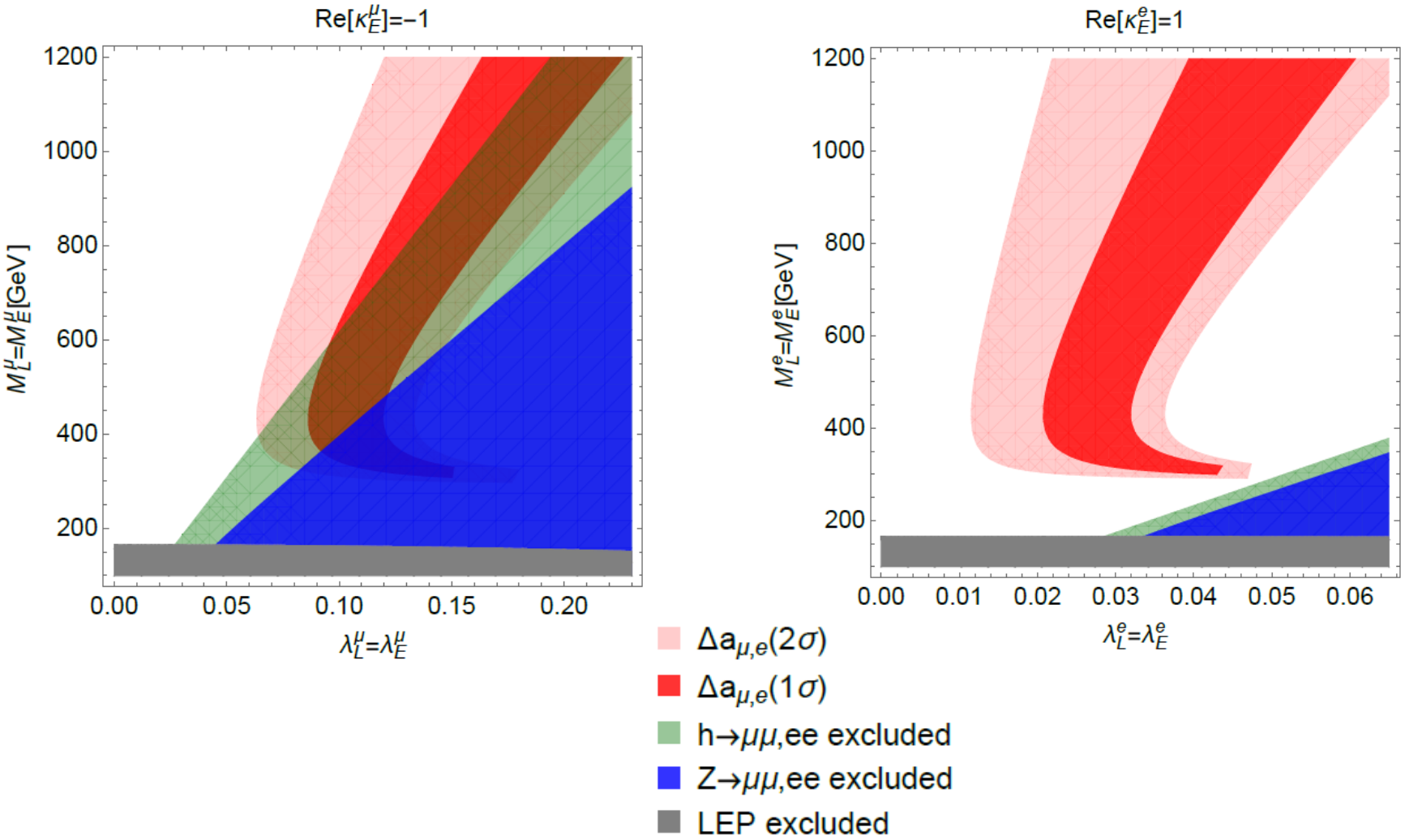
$$- \lambda_L \bar{L}_L \ell_R H - \lambda_E \bar{E}_R \tilde{H} \ell_L + \text{h.c.}$$





Chirally enhanced by $v\kappa_{L,R}/m_\mu$

Model with new vector-like leptons



Works for a_e but tension with a_μ

Modifications to the model

Universität Zürich[UZH]

- Add neutral scalar
  - Effect in a_μ possible without affecting $h \to \mu\mu$
- Impose abelian flavour symmetry (e.g. L_μ-L_τ) in order to avoid $\mu \to e\gamma$
- More minimal model with one generation of vector-like fermions possible if a_e is explained by the SM Higgs and a_μ via a new scalar
- New scalar could be L_μ-L_τ flavon

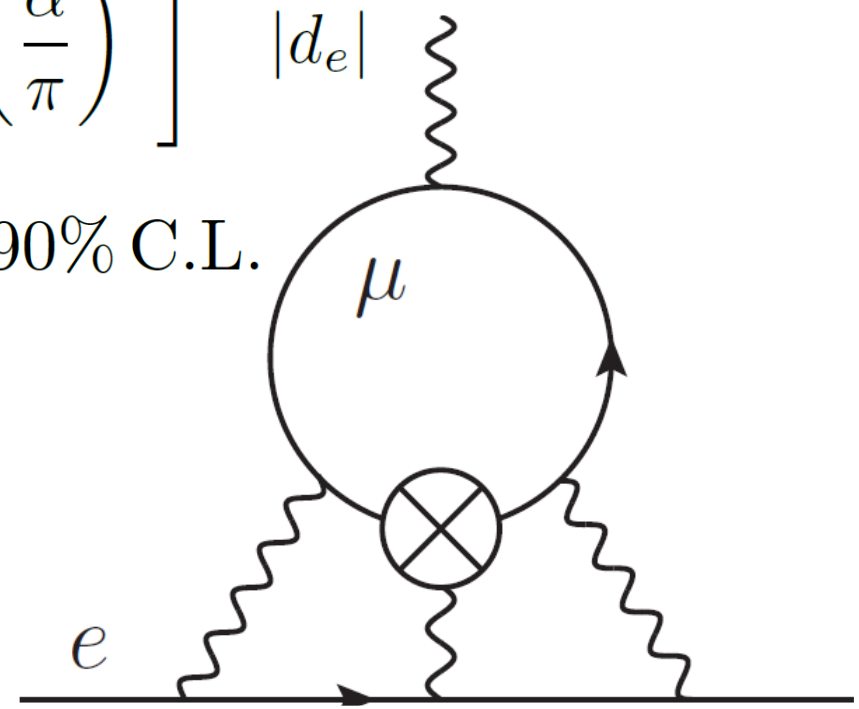
Many realizations possible

Limits on the Muon EDM

- MFV:
- Contribution only starts at the 3-loop level

$$|d_\mu| \leq \left[\left(\frac{15}{4}\zeta(3) - \frac{31}{12}\right)\frac{m_e}{m_\mu}\left(\frac{\alpha}{\pi}\right)^3\right]^{-1} |d_e|$$

$$|d_\mu| \leq 0.9 \times 10^{-19} e\,\mathrm{cm} \qquad 90\%\ \mathrm{C.L.}$$

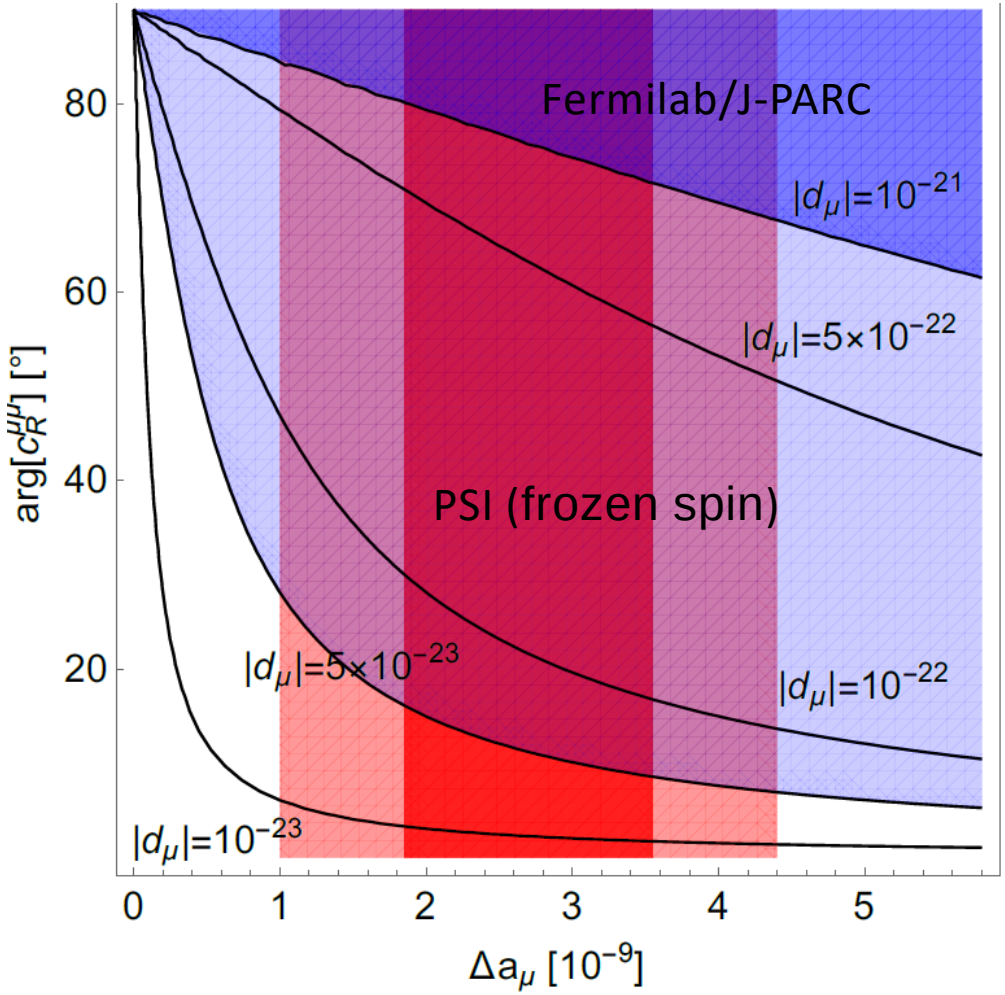


- Direct limit

$$|d_\mu| < 1.5 \times 10^{-19} e\,\mathrm{cm}$$

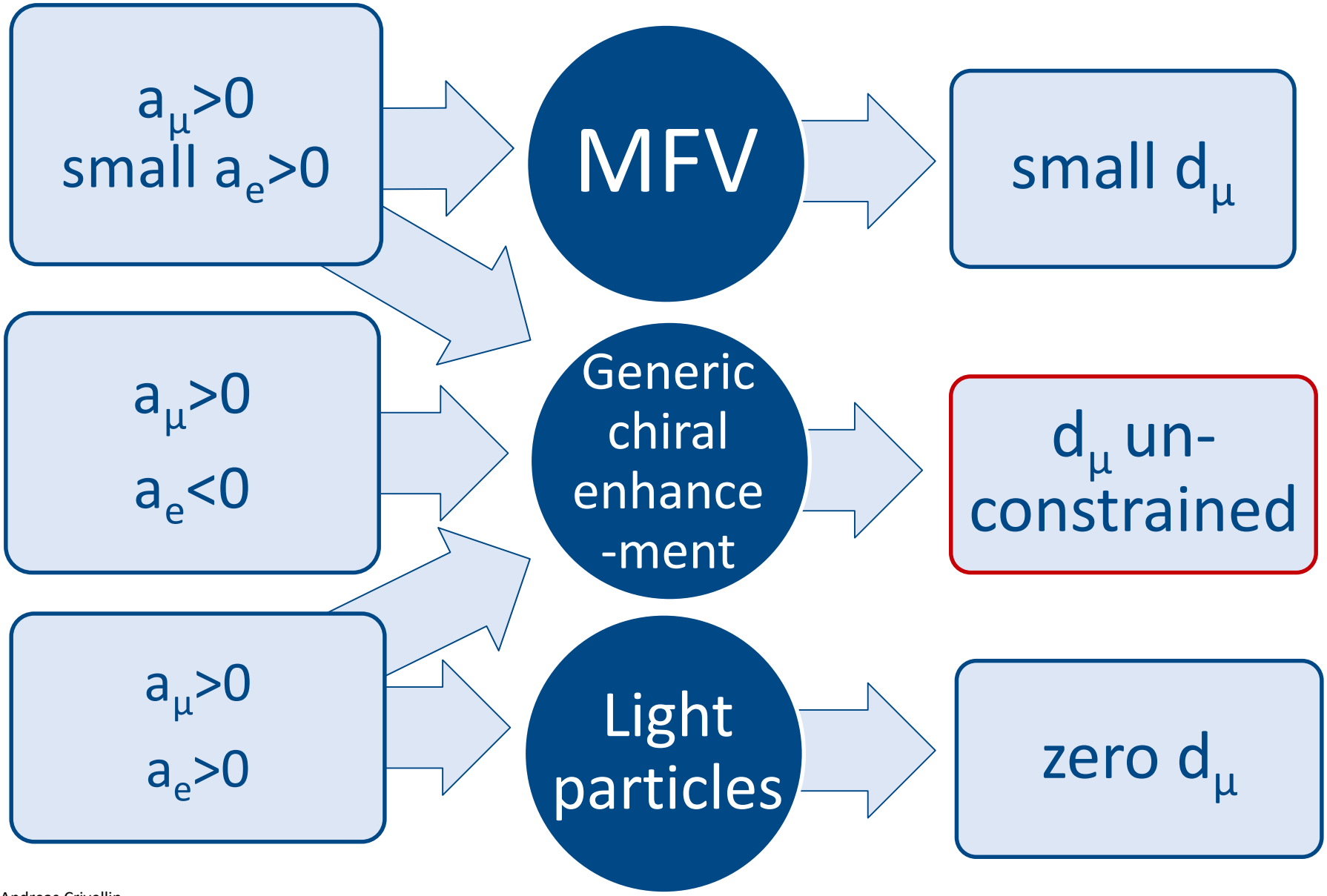
Improvement of direct limit important

Future experimental sensitivity

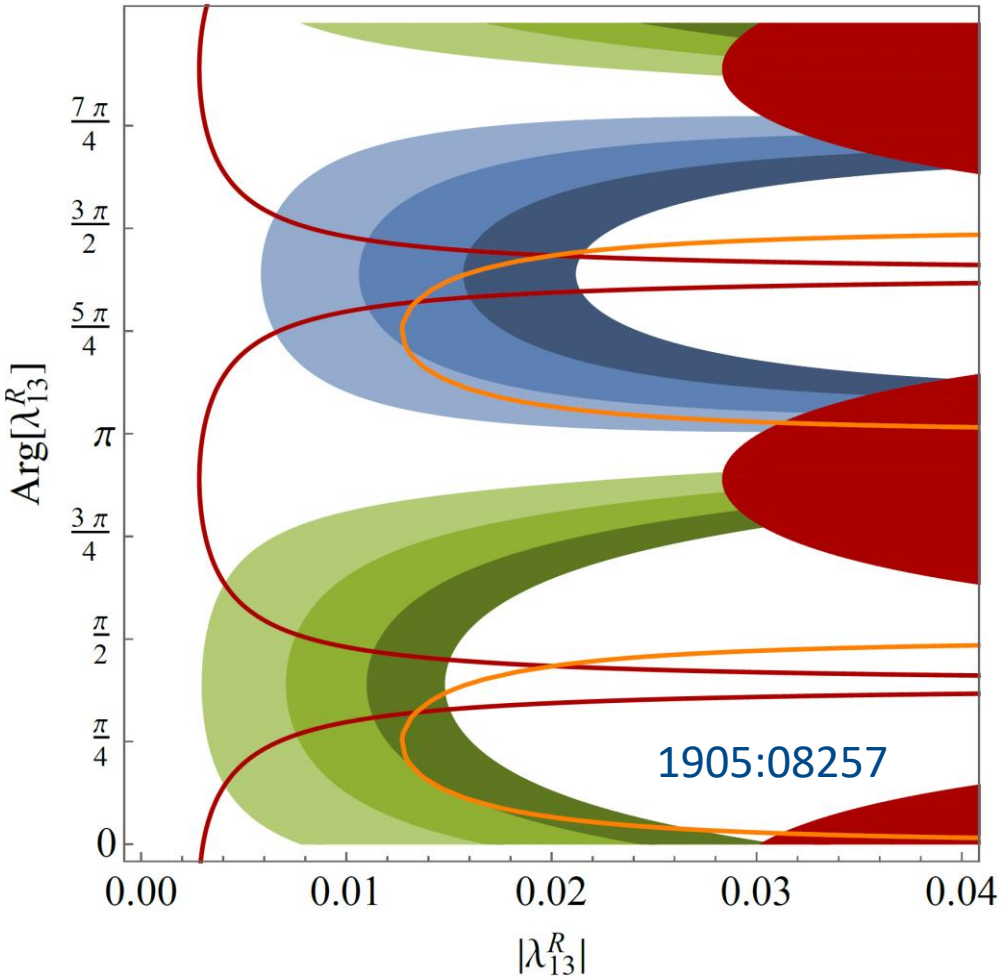


Dedicated experiment needed?!

Implications



$R(D^{(*)})$ implications for n_d



W. Dekens, J. de Vries, M. Jung, K. K. Vos, arXiv:1809.09114
AC, F. Saturnino
arxiv:1905:08257

- $0.6<\mathrm{Br}[B\to\tau\nu]/\mathrm{Br}[B\to\tau\nu]_{SM}<0.7$
- $0.7<\mathrm{Br}[B\to\tau\nu]/\mathrm{Br}[B\to\tau\nu]_{SM}<0.8$
- $0.8<\mathrm{Br}[B\to\tau\nu]/\mathrm{Br}[B\to\tau\nu]_{SM}<0.9$
- $1.1<\mathrm{Br}[B\to\tau\nu]/\mathrm{Br}[B\to\tau\nu]_{SM}<1.2$
- $1.2<\mathrm{Br}[B\to\tau\nu]/\mathrm{Br}[B\to\tau\nu]_{SM}<1.3$
- $1.3<\mathrm{Br}[B\to\tau\nu]/\mathrm{Br}[B\to\tau\nu]_{SM}<1.4$

- nEDM excluded

n2EDM sensitivity

$D^0-\bar{D}^0$ HL-LHC

Similar correlations for muon EDM?

Conclusions