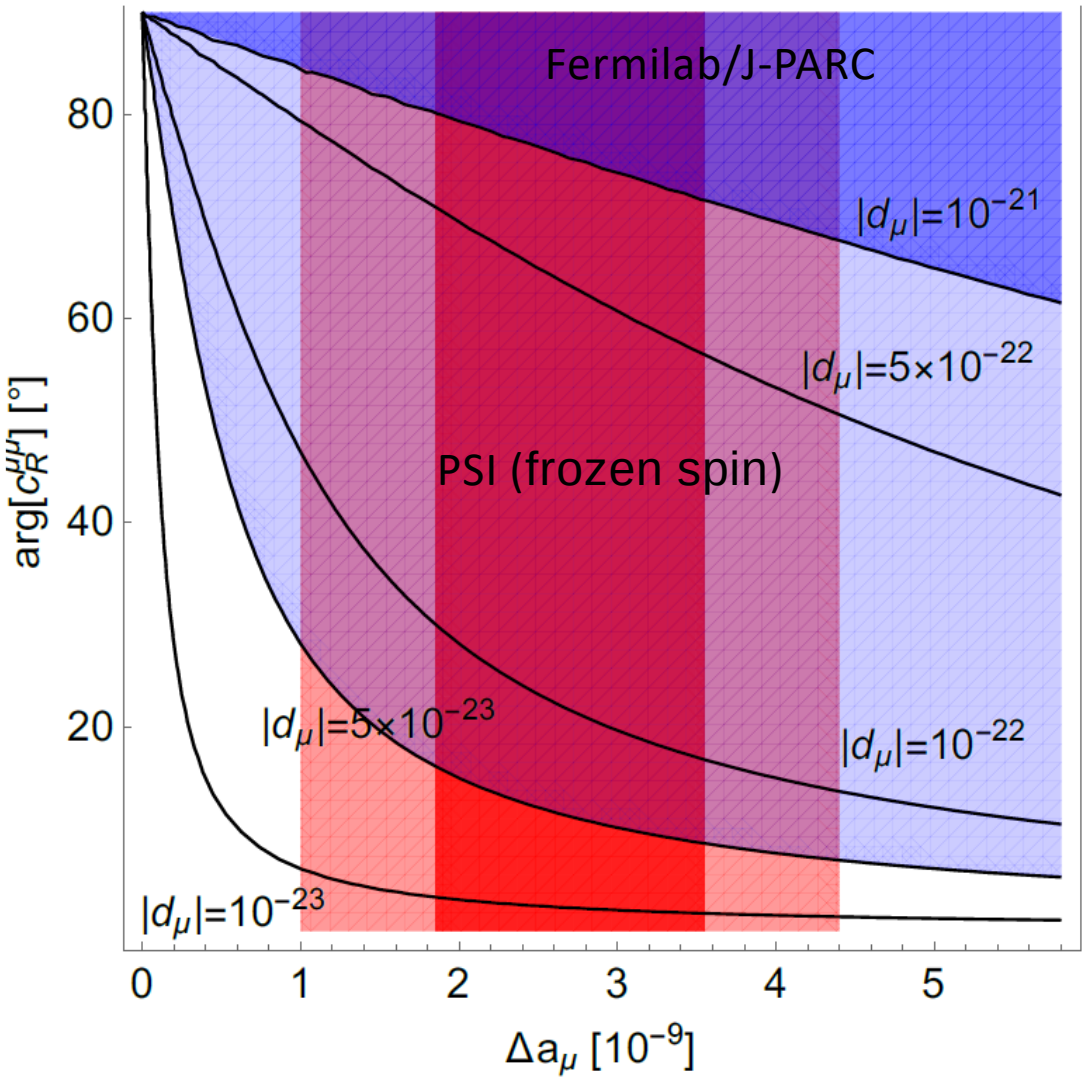
Andreas Crivellin on behalf of the Muon EDM collaboration

PSI & UZH

Why do we need a dedicated Muon EDM experiment?

PSI conference, PSI, 20.10.2022

Because no other experiment can cover the intersting region in parameter space!



A.C., M. Hoferichter, P. Schmidt-Wellenburg, PRD 2018

The PSI Muon EDM Collaboration

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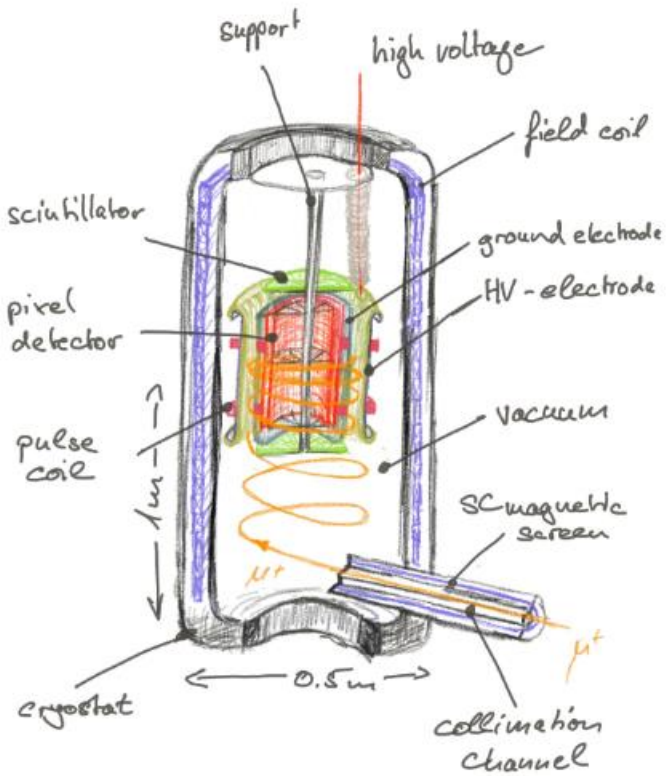
Demonstration of frozen spin technique



Phase I

$$\sigma(d_\mu)_{\mathrm{I}} = 3 \times 10^{-21}$$

Phase II

$$\sigma(d_\mu)_{\mathrm{II}} = 6 \times 10^{-23}$$

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

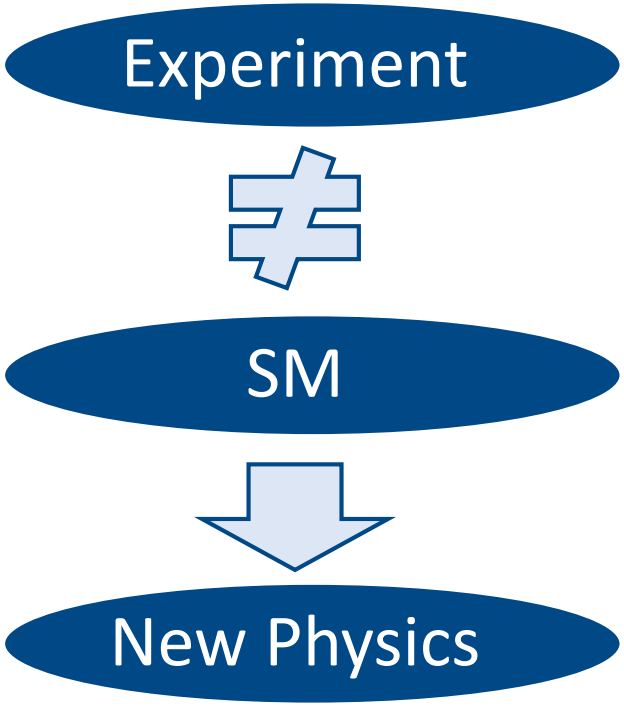
New particles and interactions exist!

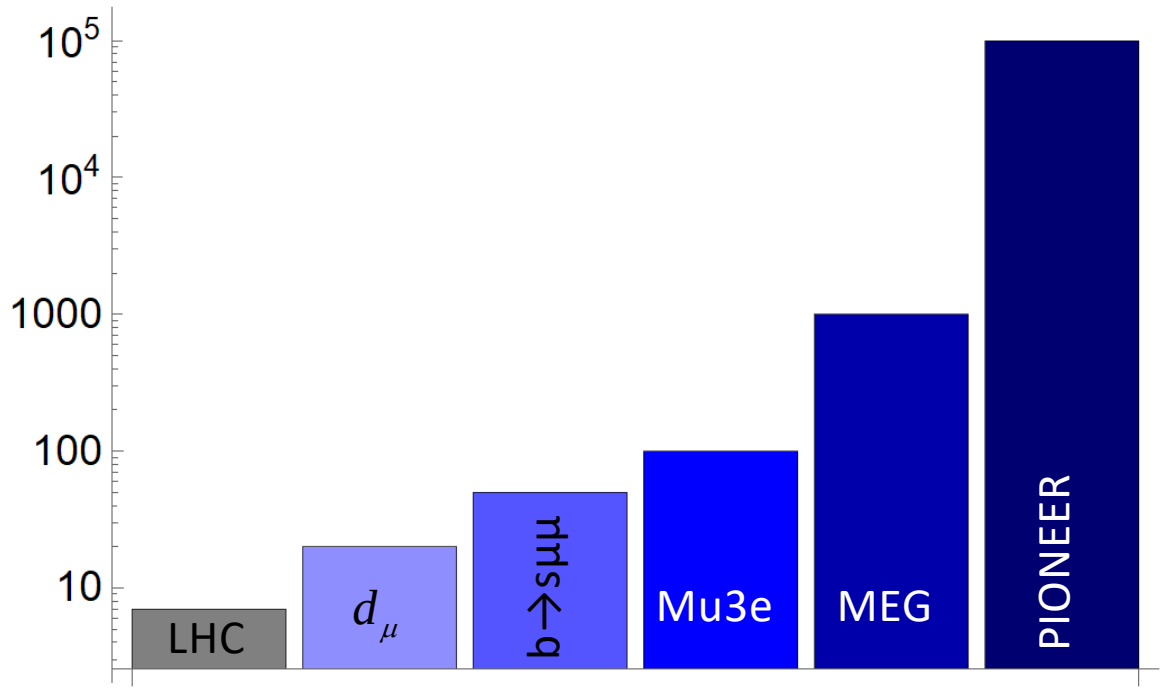
The SM must be extended!
What is the underlying fundamental theory?

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

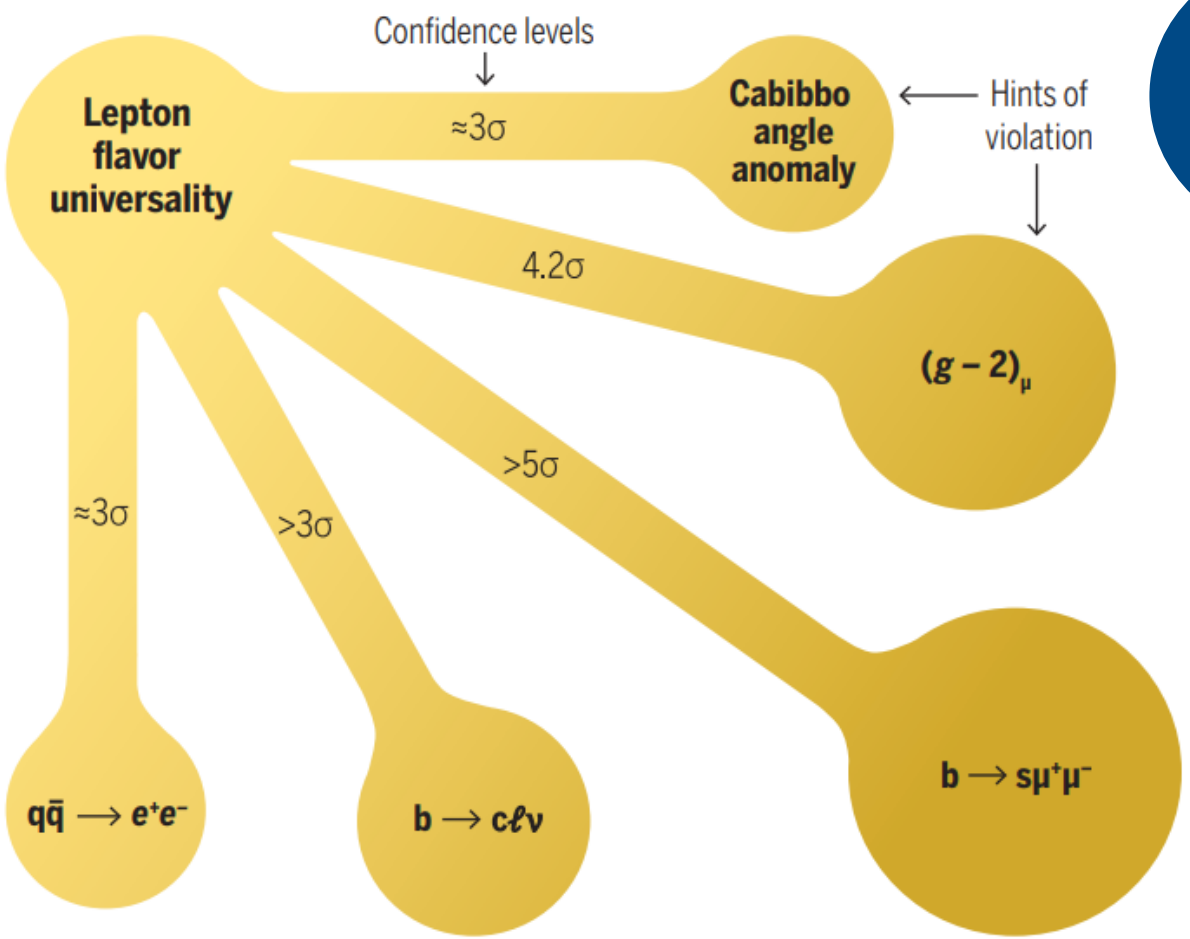




Flavour observables are sensitive to higher energy scales than collider searches

Hints for New Physics

- LFUV AC, M. Hoferichter, Science 374 (2021)



- EW observables

m_W ≈3-4σ

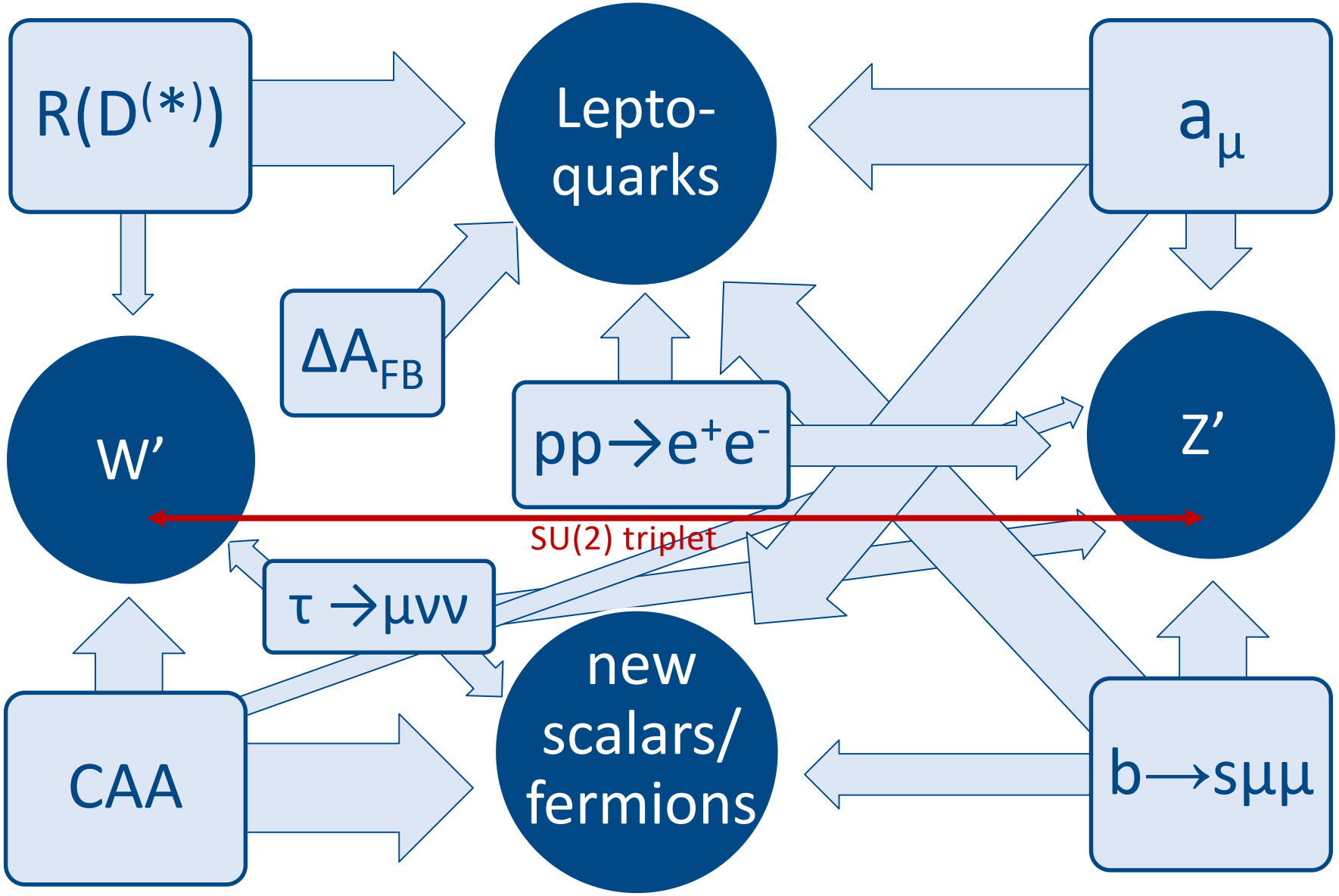
$Z \to bb$

- Direct searches

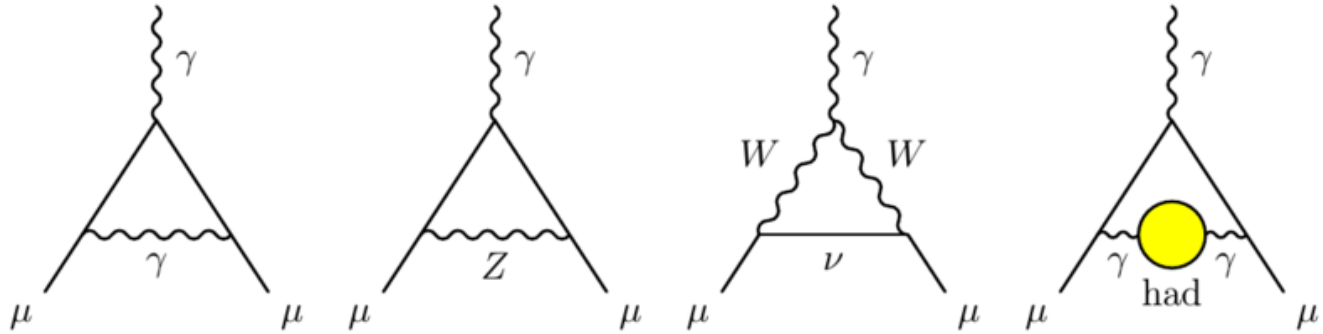
γγ
ττ

bbγγ
WW
jj(jj)

Explanations



Muon Anomalous Magnetic Moment



- Precision test of the SM

See talk of Martin Hoferichter

- Sensitive to chirality violation
- Theory prediction challenging (hadronic effects)

$$\Delta a_\mu = (279 \pm 76) \times 10^{-11}$$

T. Aoyama et al., arXiv:2006.04822

- New experimental results from Fermilab (today!)
- Vanishes for $m_\mu \to 0$ ⇨ **measure of LFUV**

4.2σ deviation from the SM prediction?

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)
  - ALP (axion like particle)
- Chiral enhancement: Chirality flip does not come from the muon mass but rather from a NP mass inside the loop

Light particles or/and chiral enhancement

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_Ψ A charge, mass of the fermion $\quad f, g$ A loop functions

- MSSM: (tan(ß))
- 2HDM: m_τ/m_μ poster of George Hou
- Leptoquarks: m_t/m_μ
- Model with vector like fermions: m_Ψ/m_μ

A priori arbitrary phase ➡ muon EDM

Limits on the Muon EDM

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- MFV: $|d_\mu^{\mathrm{MFV}}| < 2.3 \times 10^{-27} e\,\mathrm{cm} \qquad 90\%\ \mathrm{C.L.}$
- Contribution only starts at the 3-loop level

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

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

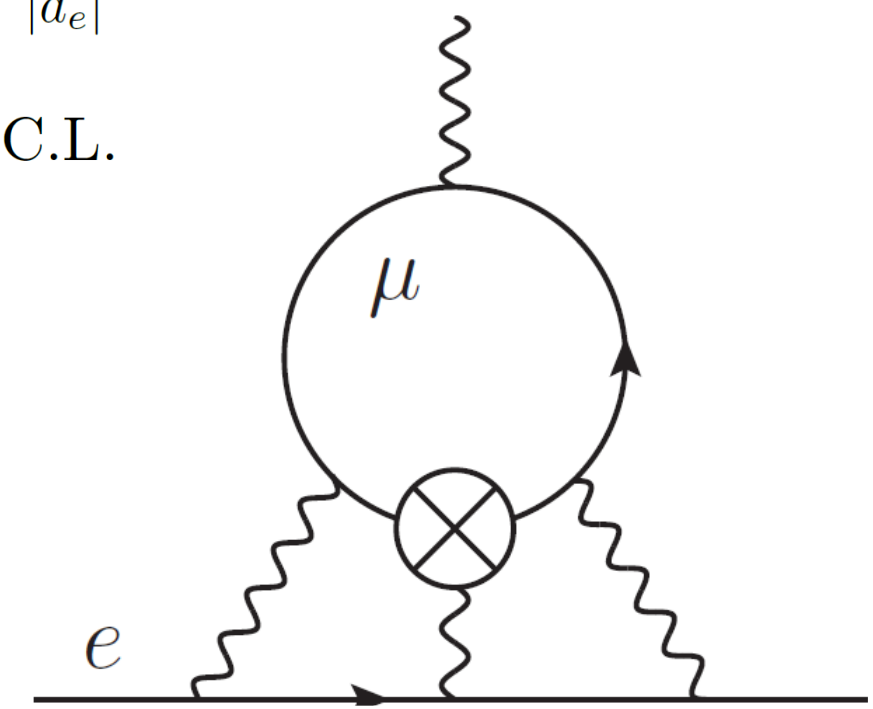
- arXiv:2108.05398

$$d_\mu(^{199}\mathrm{Hg}) < 6 \times 10^{-20} \mathrm{ecm}$$

$$d_\mu(\mathrm{ThO}) < 2 \times 10^{-20} \mathrm{ecm},$$

- Direct limit

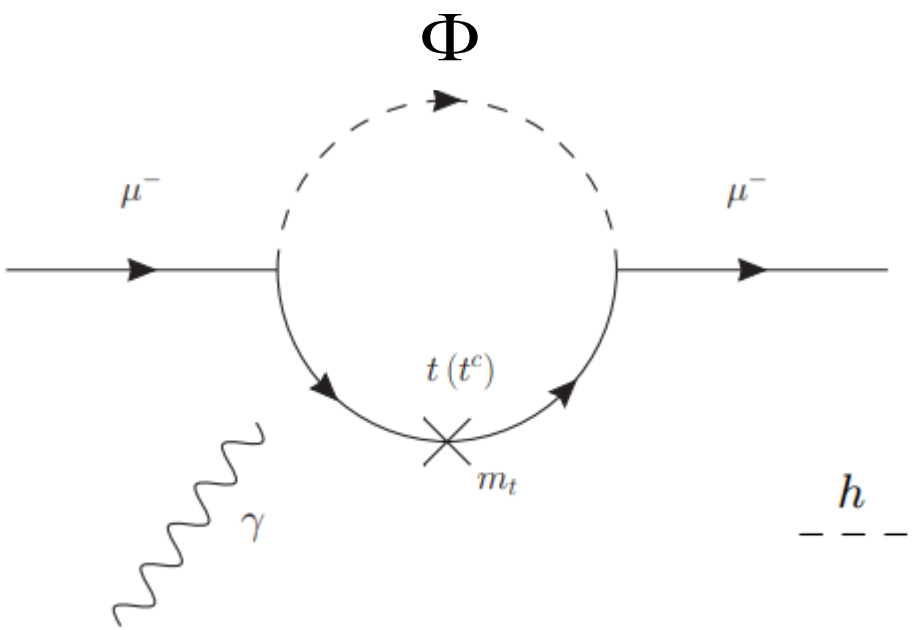
$$|d_\mu| < 1.5 \times 10^{-19} e\,\mathrm{cm}$$

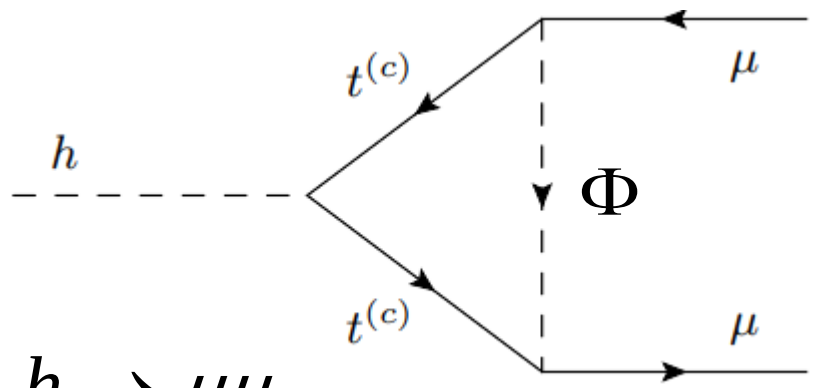


Improvement of direct limit important

Leptoquarks in a_μ

- Chirally enhanced effects via top-loops



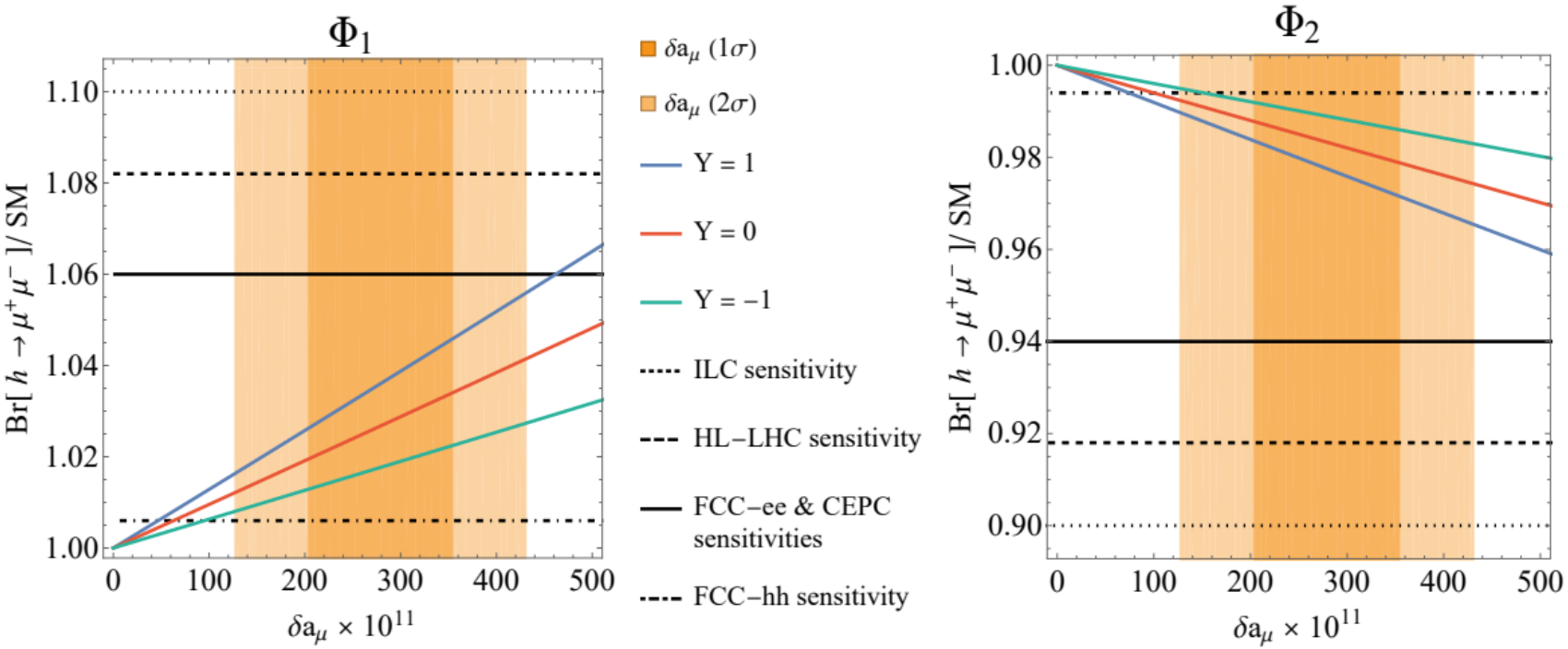


- m_t/m_μ enhanced effect $h \to \mu\mu$
- m_t^2/m_Z^2 enhanced effect in $Z \to \mu\mu$

Correlations with h→μμ and Z→μμ

a_μ vs $h \to \mu\mu$

- Chirally enhanced effects via top-loops
- Same coupling structure → direct correlation

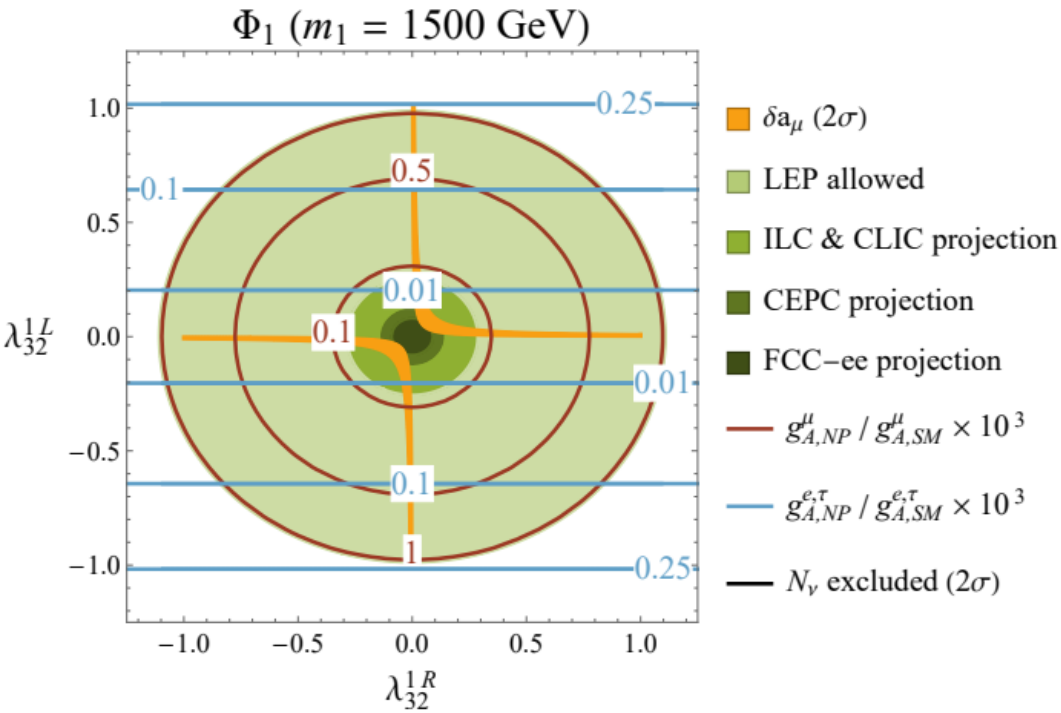


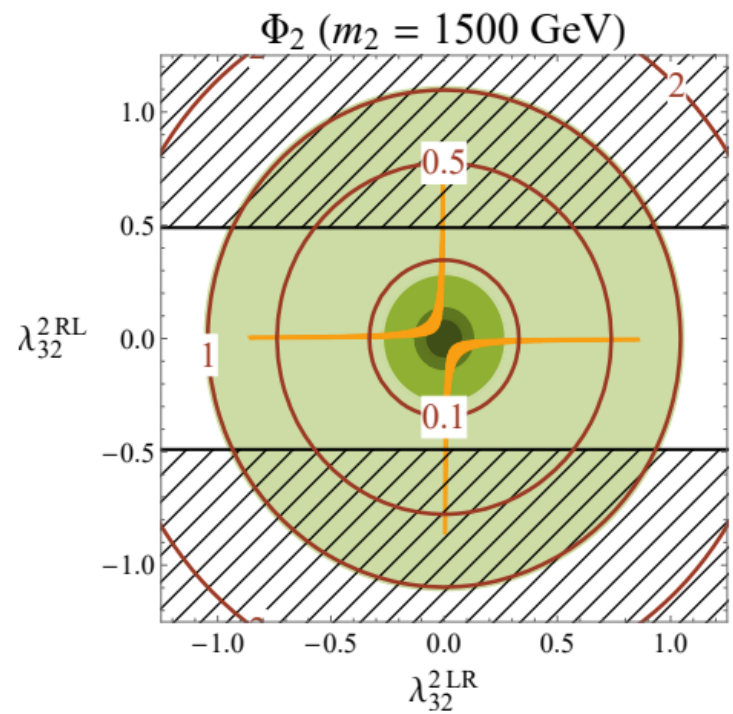
A.C., D. Mueller, F. Saturnino, PRL 2021

$h \to \mu\mu$ at future colliders

a_μ vs $Z\to\mu\mu$

- Chirally enhanced effects via top-loops





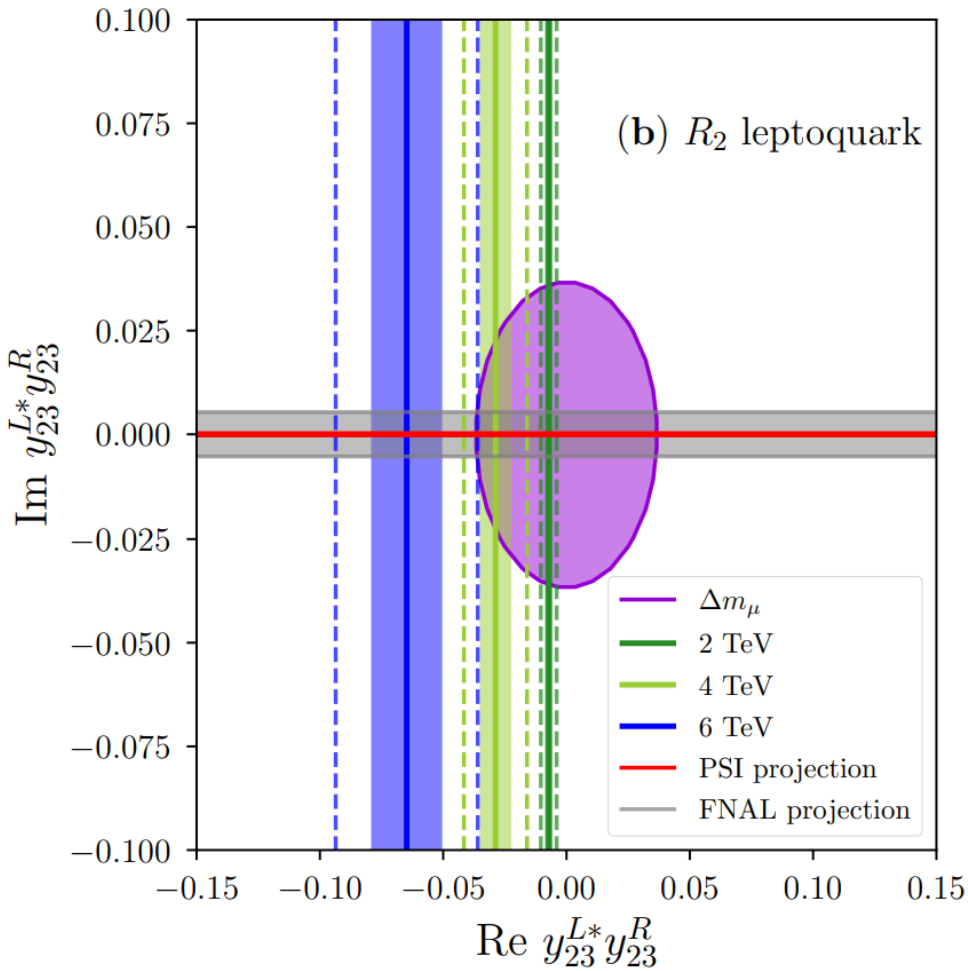
$\lambda_\mu^{L,R}$ Left-, right-handed muon-top coupling

E. Leskow, A.C., G. D'Ambrosio, D. Müller 1612.06858
A.C, C. Greub, D. Müller, F.Saturnino, 2010.06593

$Z\to\mu\mu$ at future colliders

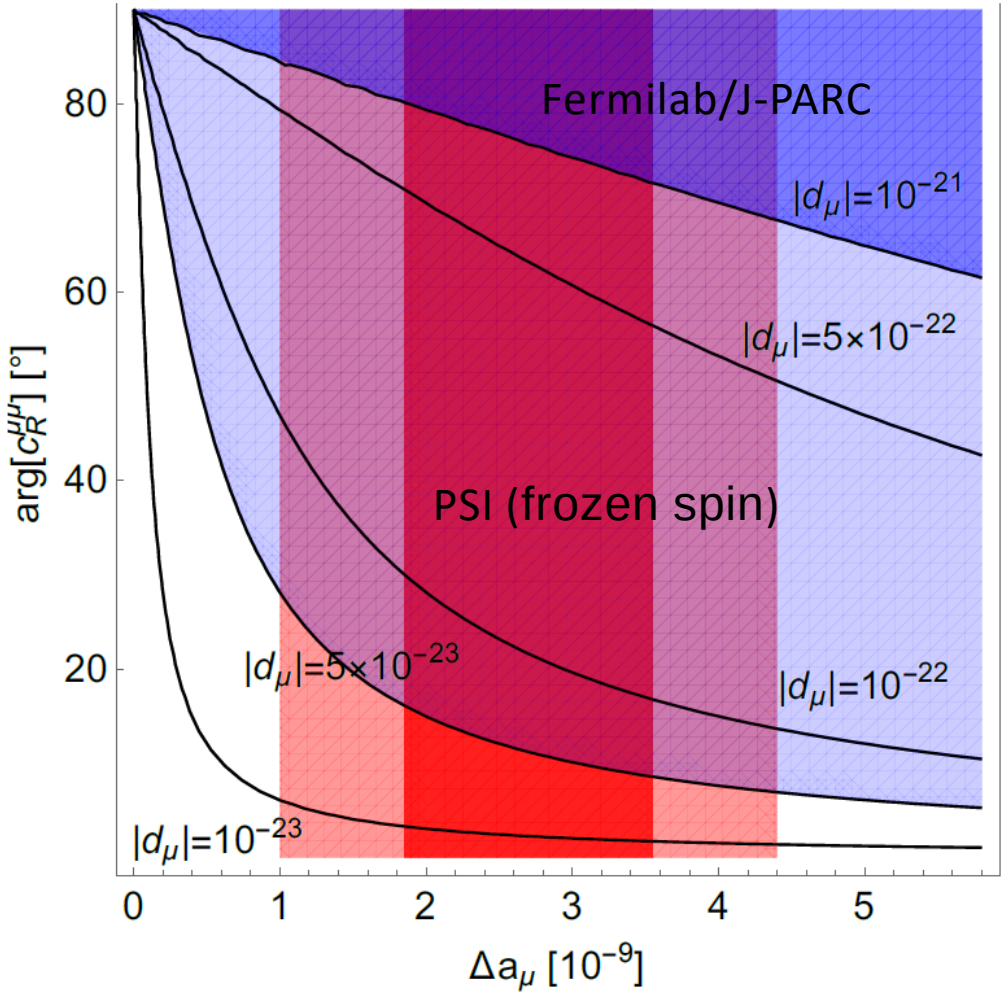
Fine-Tuning?

Bigaran, Volkas, 2110.03707



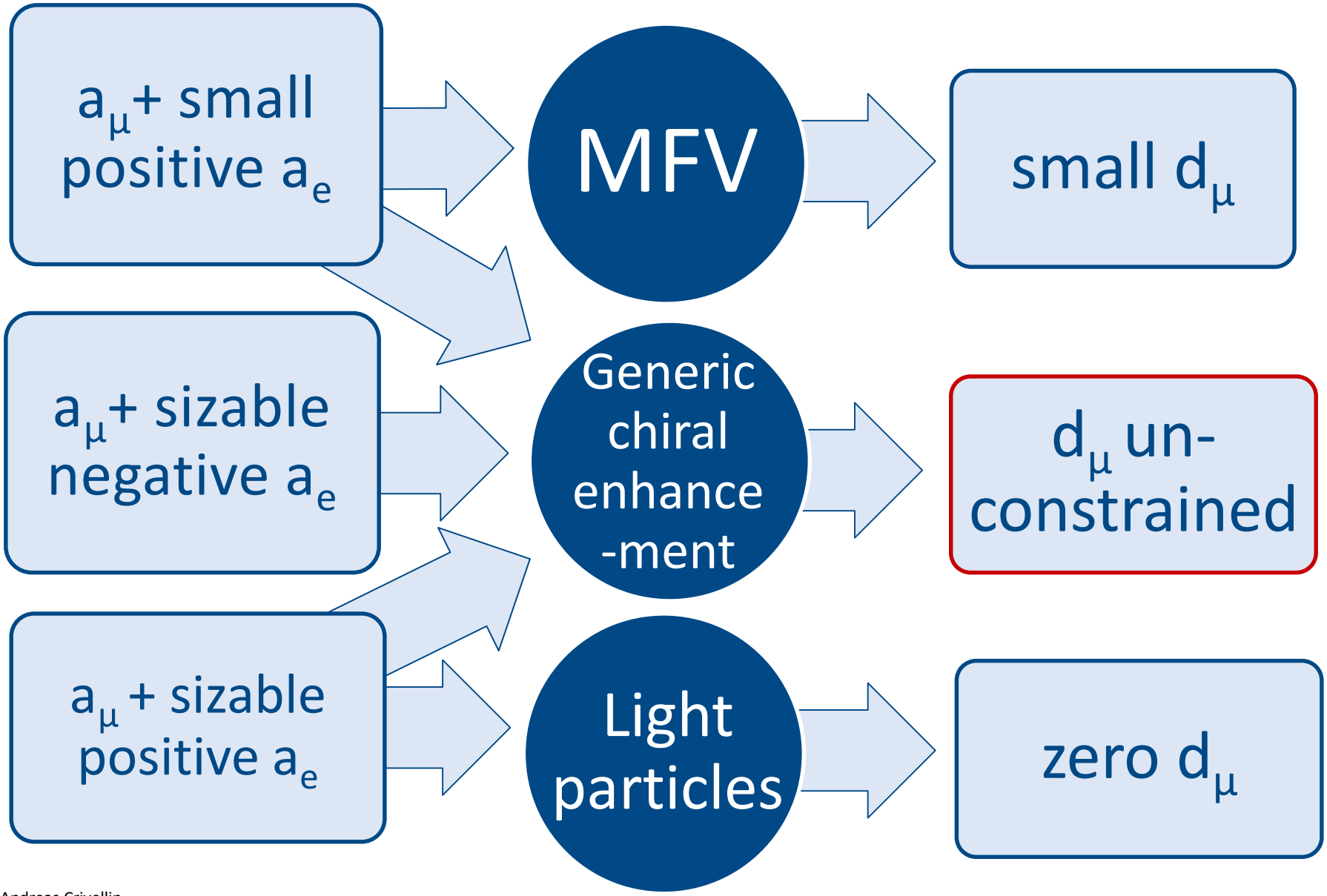
No signifcant tuning necessary

Future experimental sensitivity

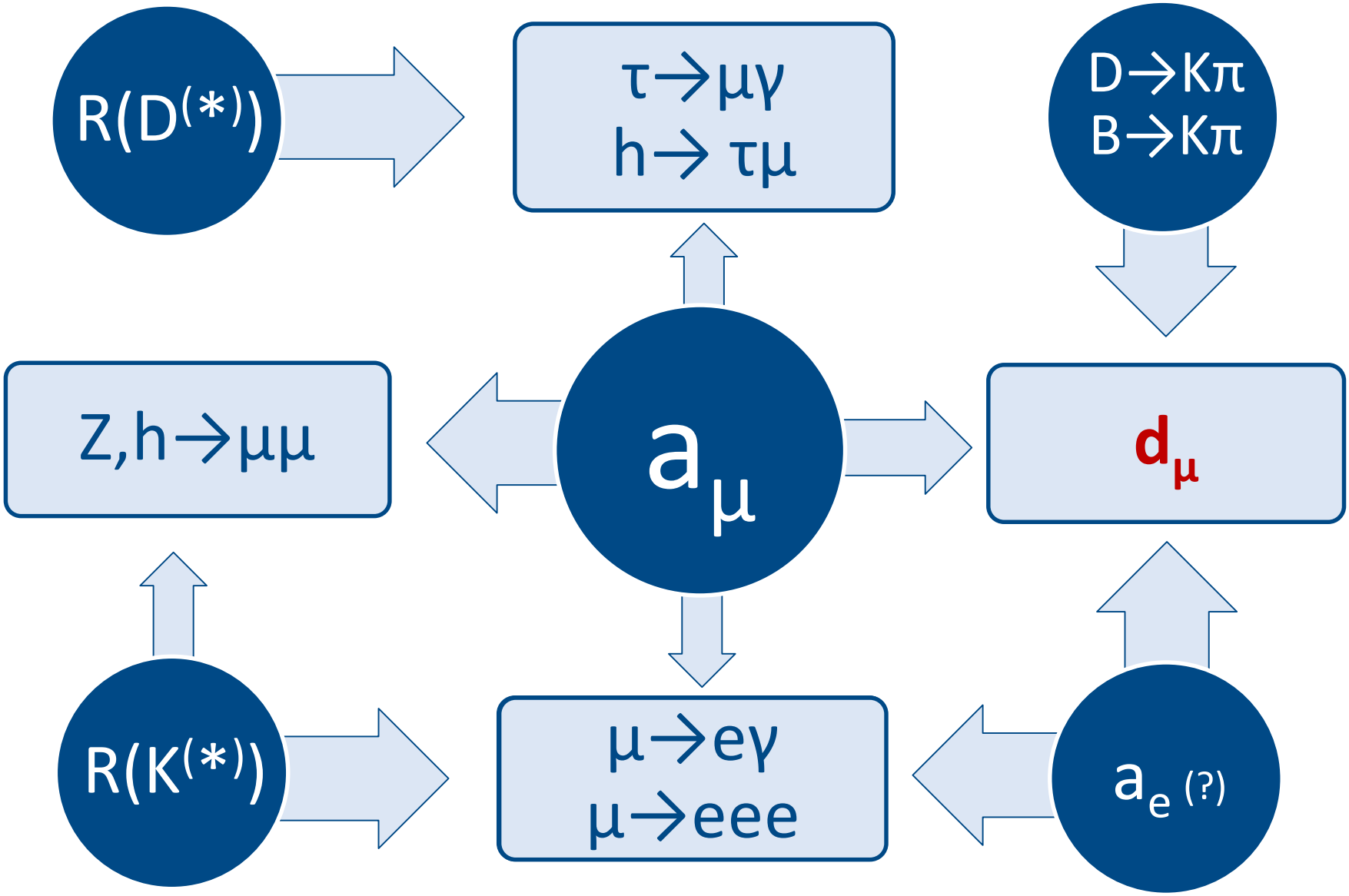


Dedicated experiment needed!

Implications of the Muon EDM



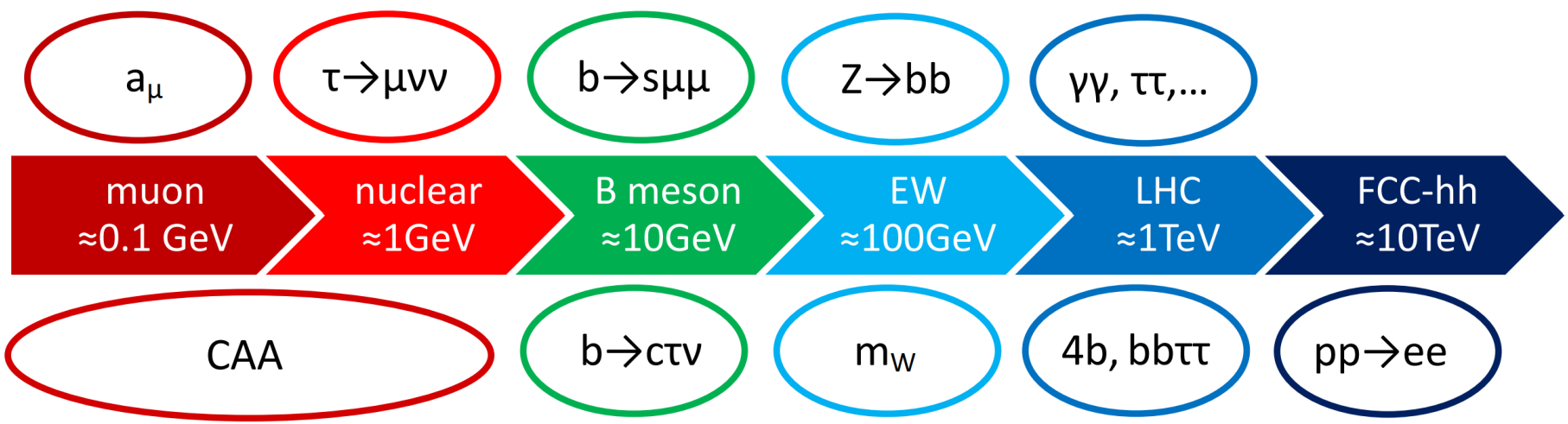
Implications and future directions



Conclusions

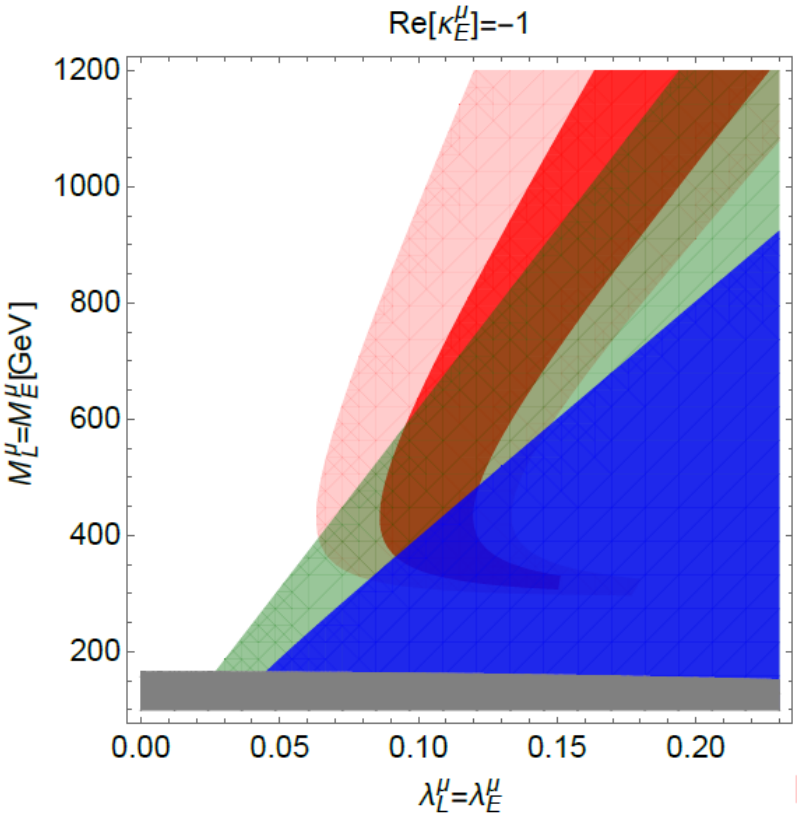
- Many intriguing anomalies emerged in the last years:
  - LFUV
  - EW observables
  - Direct LHC searches

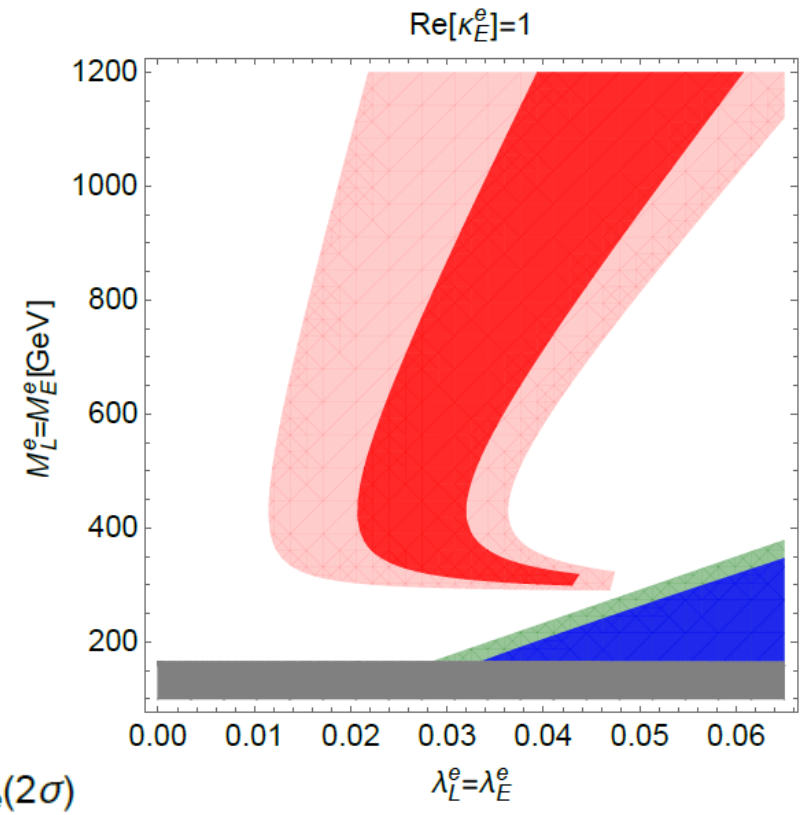
The muon EDM experiment can play an decisive role proving BSM physics



Backup

Model with new vector-like leptons

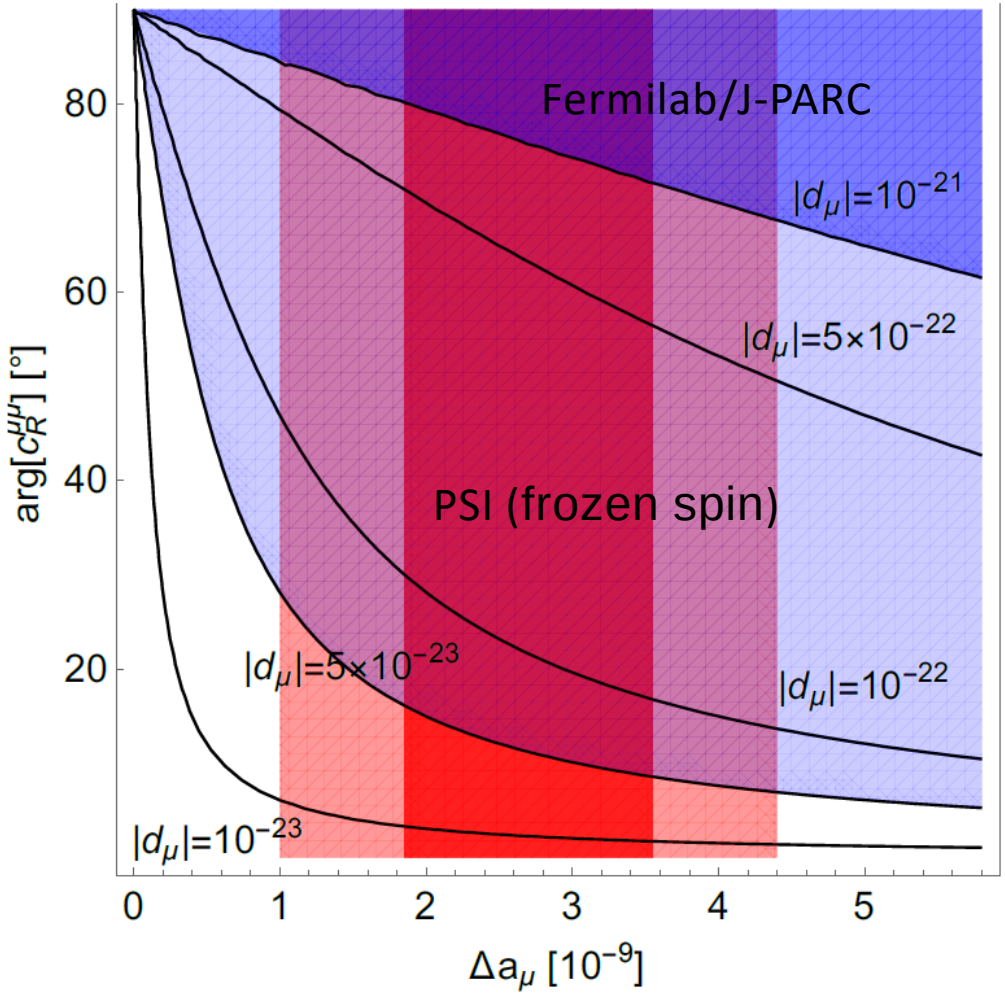




- $\Delta a_{\mu,e}(2\sigma)$
- $\Delta a_{\mu,e}(1\sigma)$
- h→$\mu\mu$,ee excluded
- Z→$\mu\mu$,ee excluded
- LEP excluded

Works for a_e but tension with a_μ

Future experimental sensitivity



Dedicated experiment needed?

Models for a common explanation

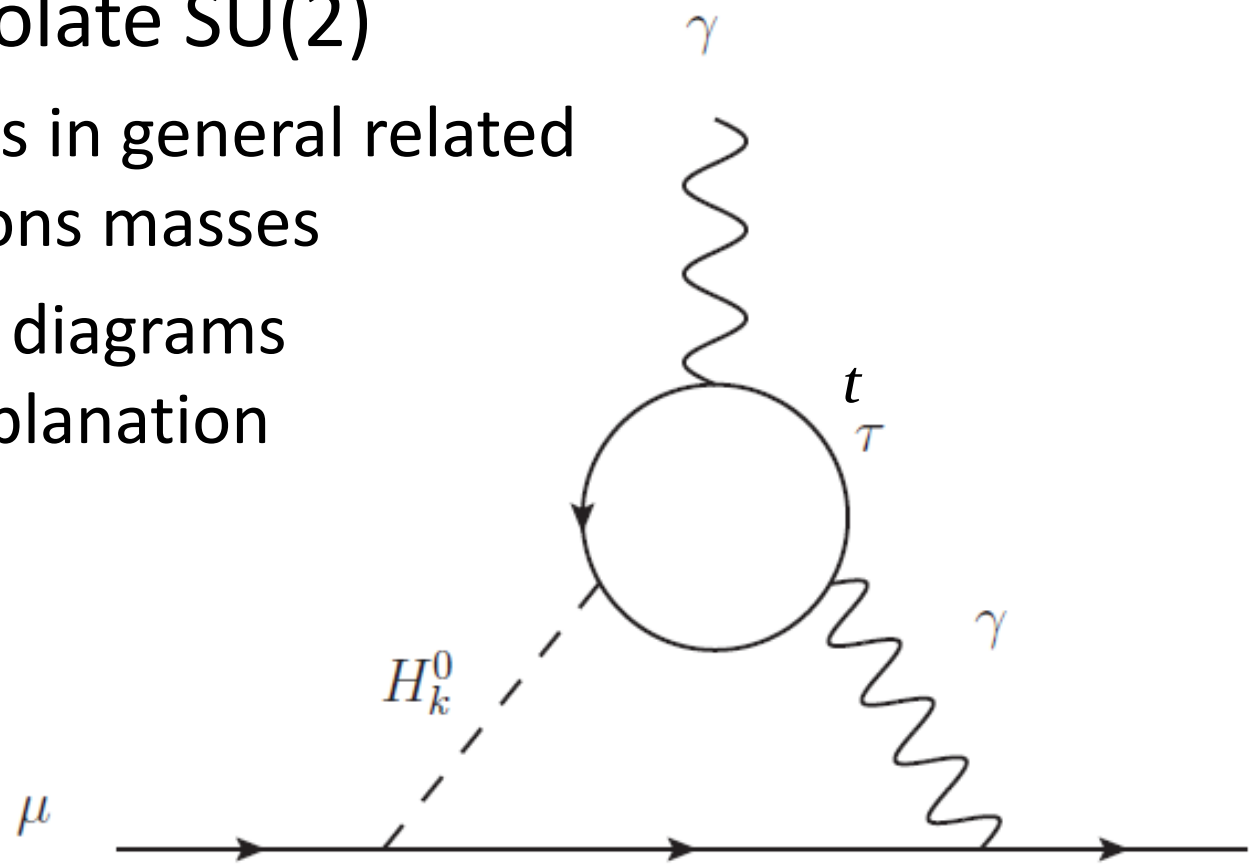
Universität Zürich[UZH]

- 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

2HDM via Barr-Zee

- Scalars: violate SU(2)
  - Couplings in general related to fermions masses
  - Barr-Zee diagrams make explanation possible



Explanation difficult but possible

Modifications to the model

- 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

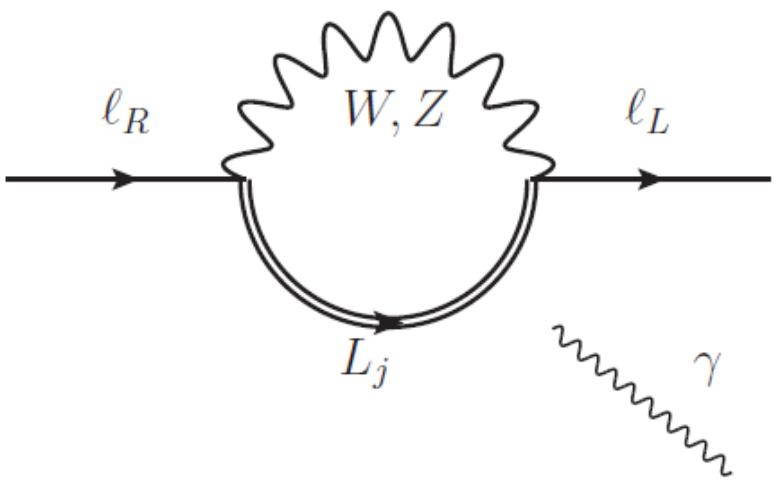
Many realizations possible

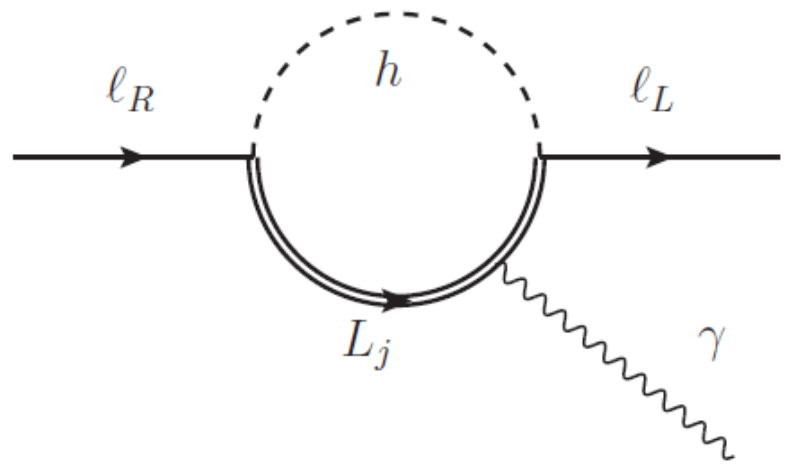
Model with new vector-like leptons

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

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

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





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

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

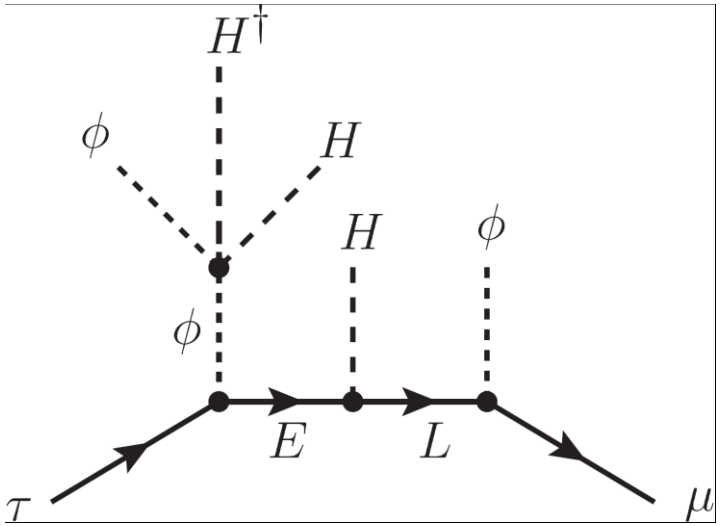
- MSSM: (tan(ß))
- Leptoquarks: m_t/m_μ
- Model with vector like fermions: m_Ψ/m_μ

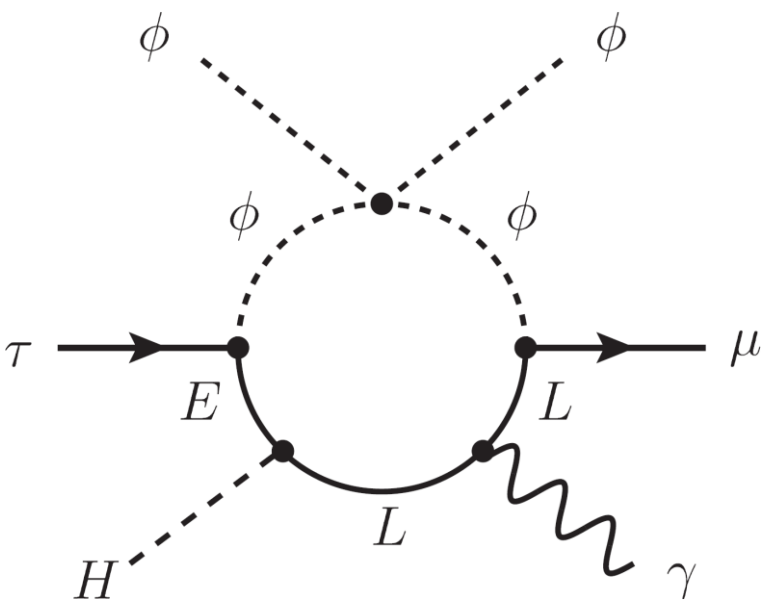
Enhancement from new sources of EW breaking

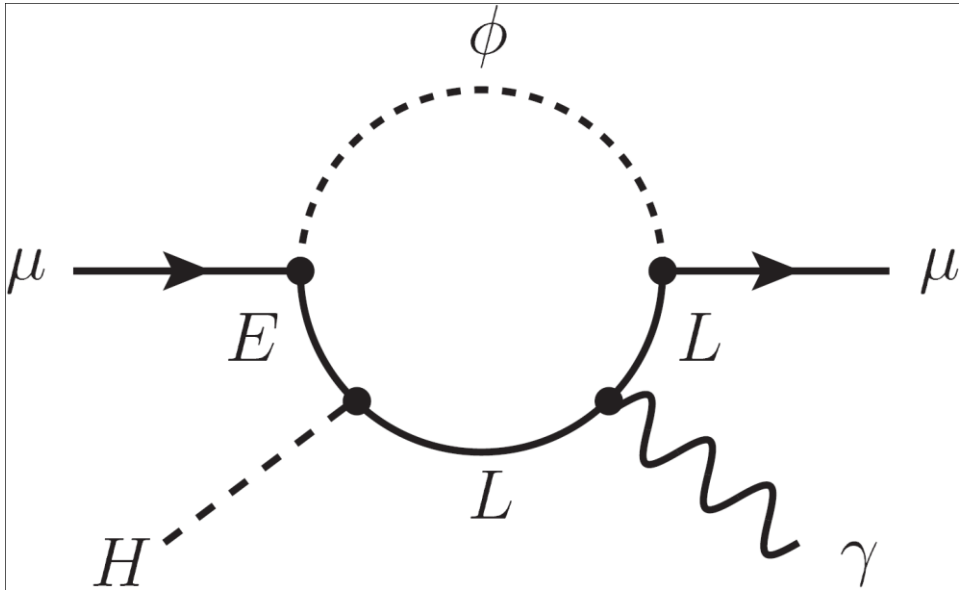
L_μ-L_τ model for a_μ and $h \to \tau\mu$

W. Altmannshofer, M. Carena, AC, 1604.08221

- L_μ-L_τ flavour symmetry
- Flavon mixes with the Higgs
- $\tau \to \mu\gamma$ is protected
- a_μ is not protected
- Effects in $h \to \mu\mu$





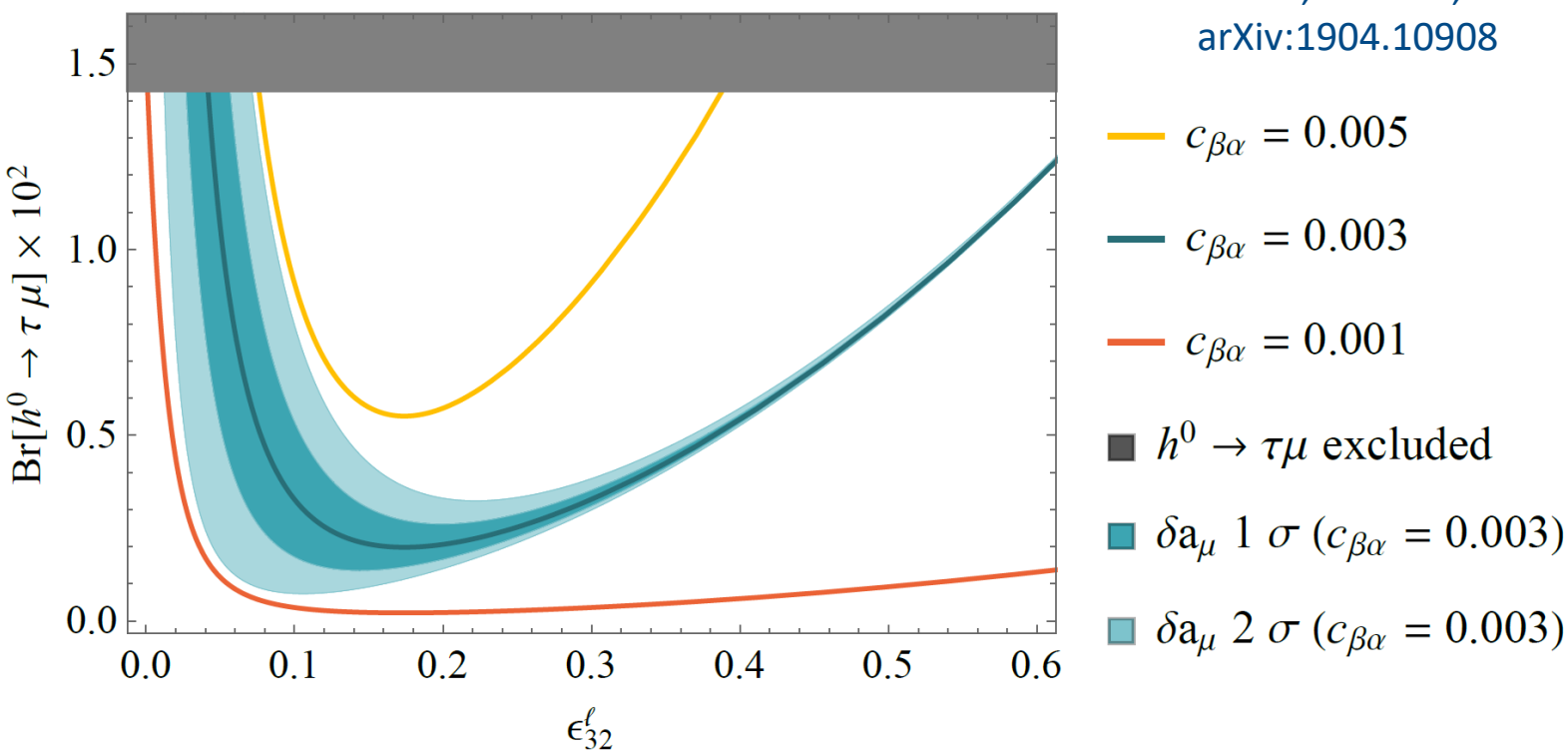


2HDMs

- Chirally enhancement of m_τ/m_μ

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

Y. Abe, T. Toma, K. Tsumura
arXiv:1904.10908



Unavoidable constraints from h→τμ