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a_μ: Beyond the Standard Model

Seattle, 09.09.2019

Outline

- Introduction: Searching for new physics with flavour
- Explaining the anomalous magnetic moment of the muon with new physics
- a_μ and consequences for future measurements
- Correlations with the electron AMM and implications for the muon EDM
- Further Flavour anomalies and future prospects

Physics Beyond the Standard Model

- 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

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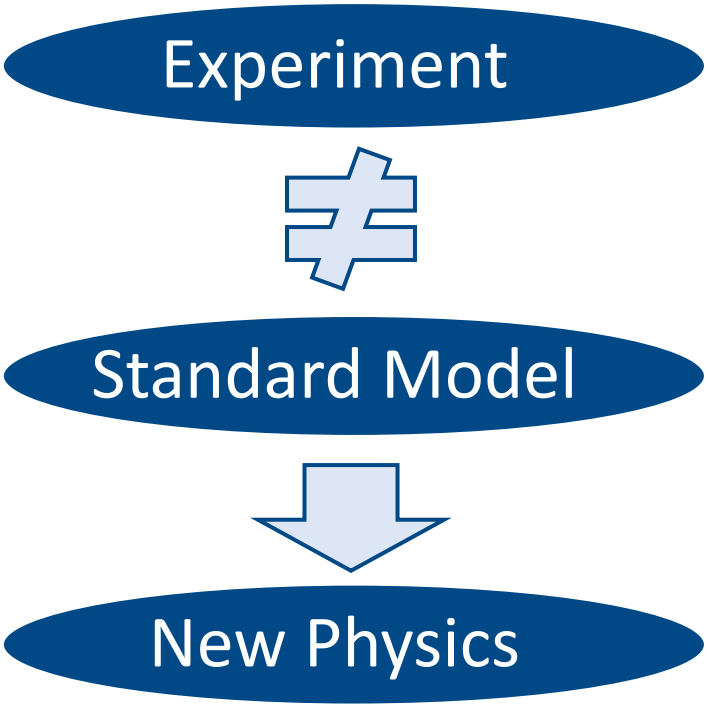
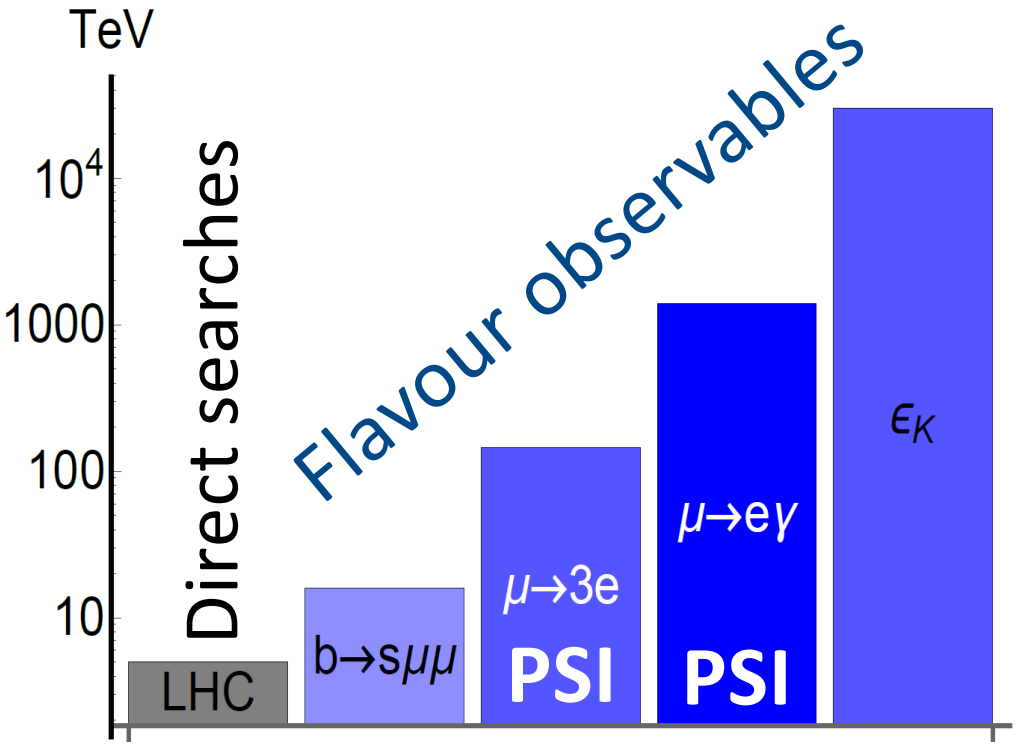
- At colliders one produces many (up to 10^{14}) heavy quarks or leptons and measures their decays into light flavours





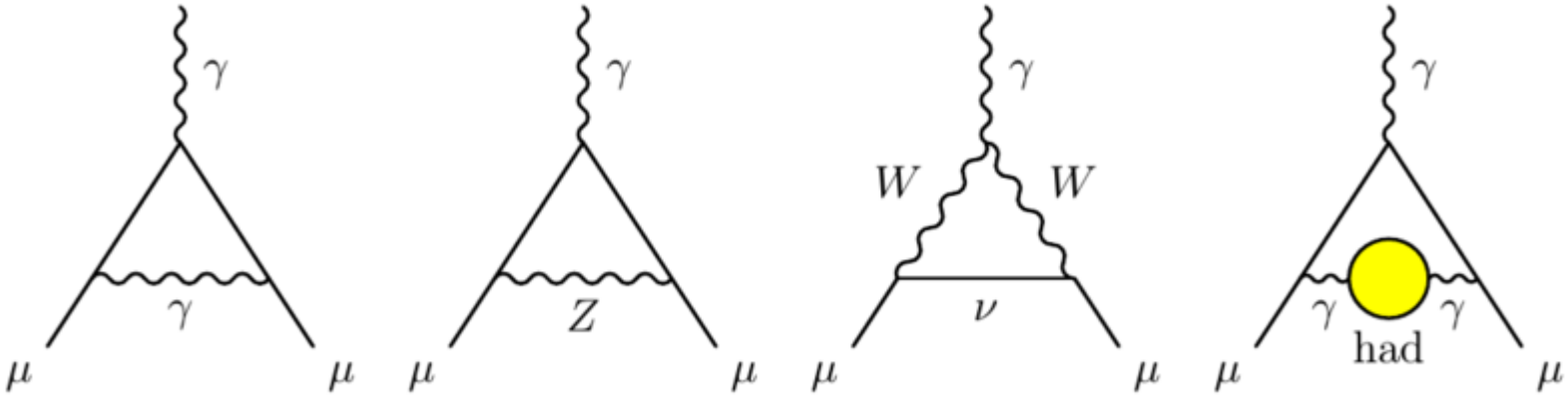
Flavour observables are sensitive to higher energy scales than collider searches

Muon Anomalous Magnetic Moment

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

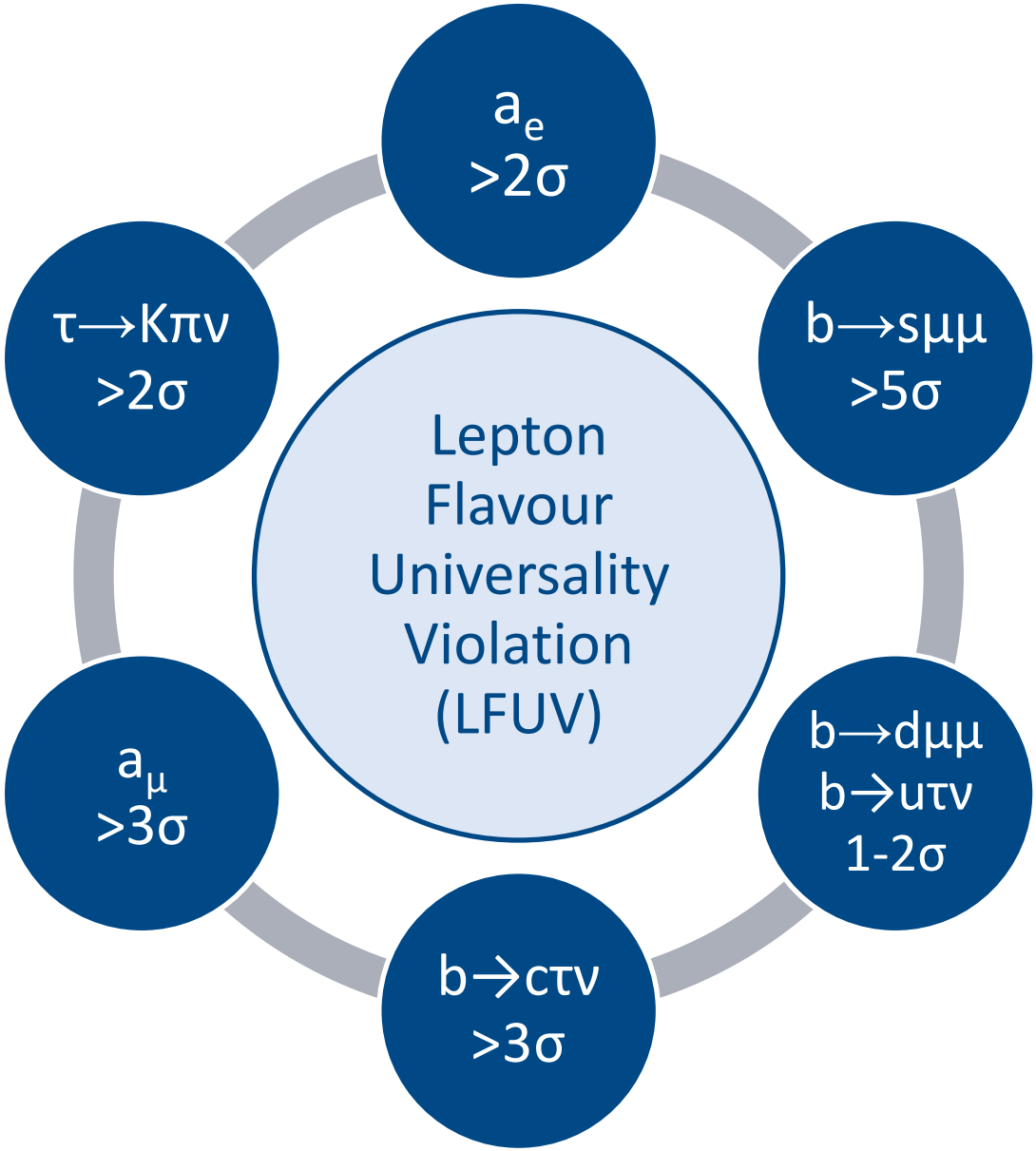
$$\Delta a_\mu \approx 270(85)\times 10^{-11}$$

- Soon new experimental results from Fermilab



3σ deviation (order of SM-EW contribution)

a_μ and further hints for New Physics



Probability for statistical fluctuation < 0.0001%

ε'/ε
≈3σ

B→Kπ
>2σ

Dipoles in the EFT

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- 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

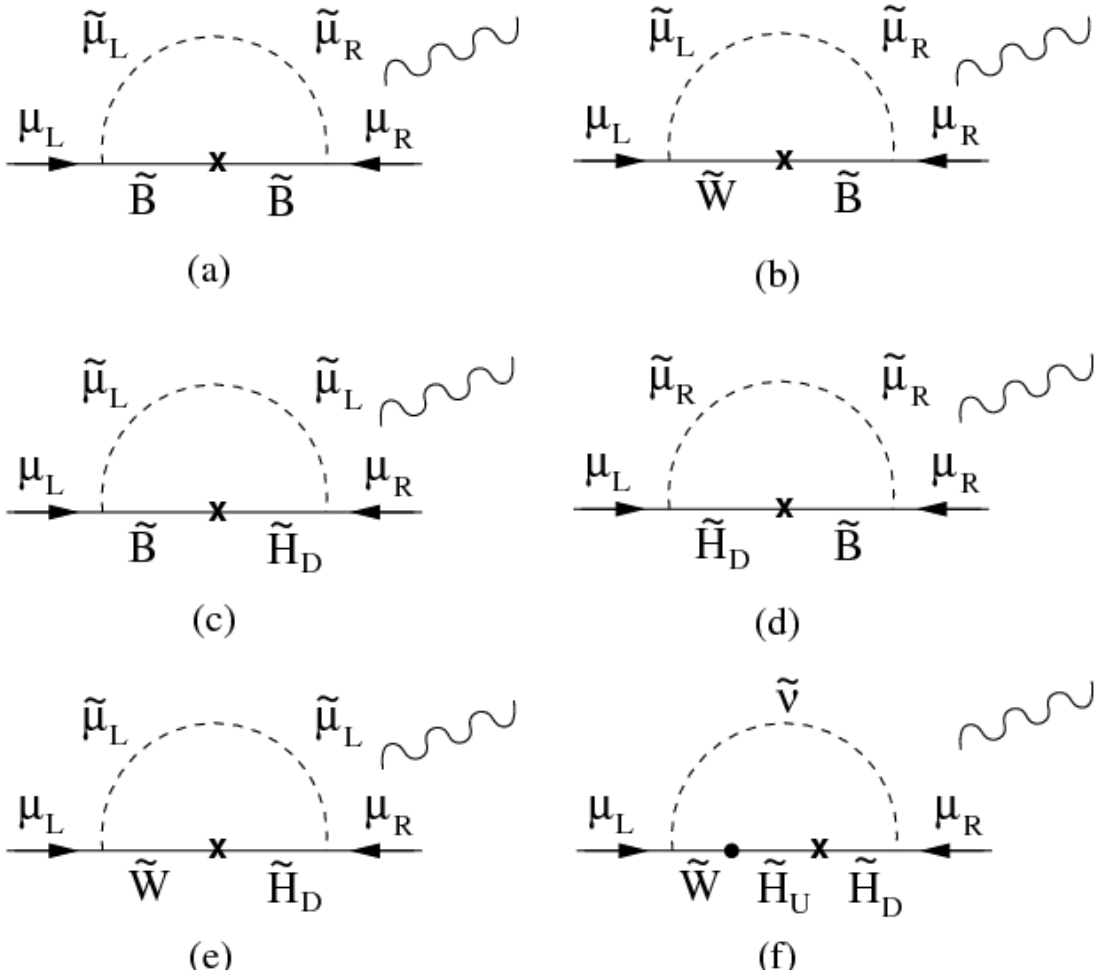
- Light particles
  - Neutral scalars
  - Neutral vector (Z' Dark Photon)
  - ALP (axion like particle)

Huge literature

- 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

a_μ: MSSM

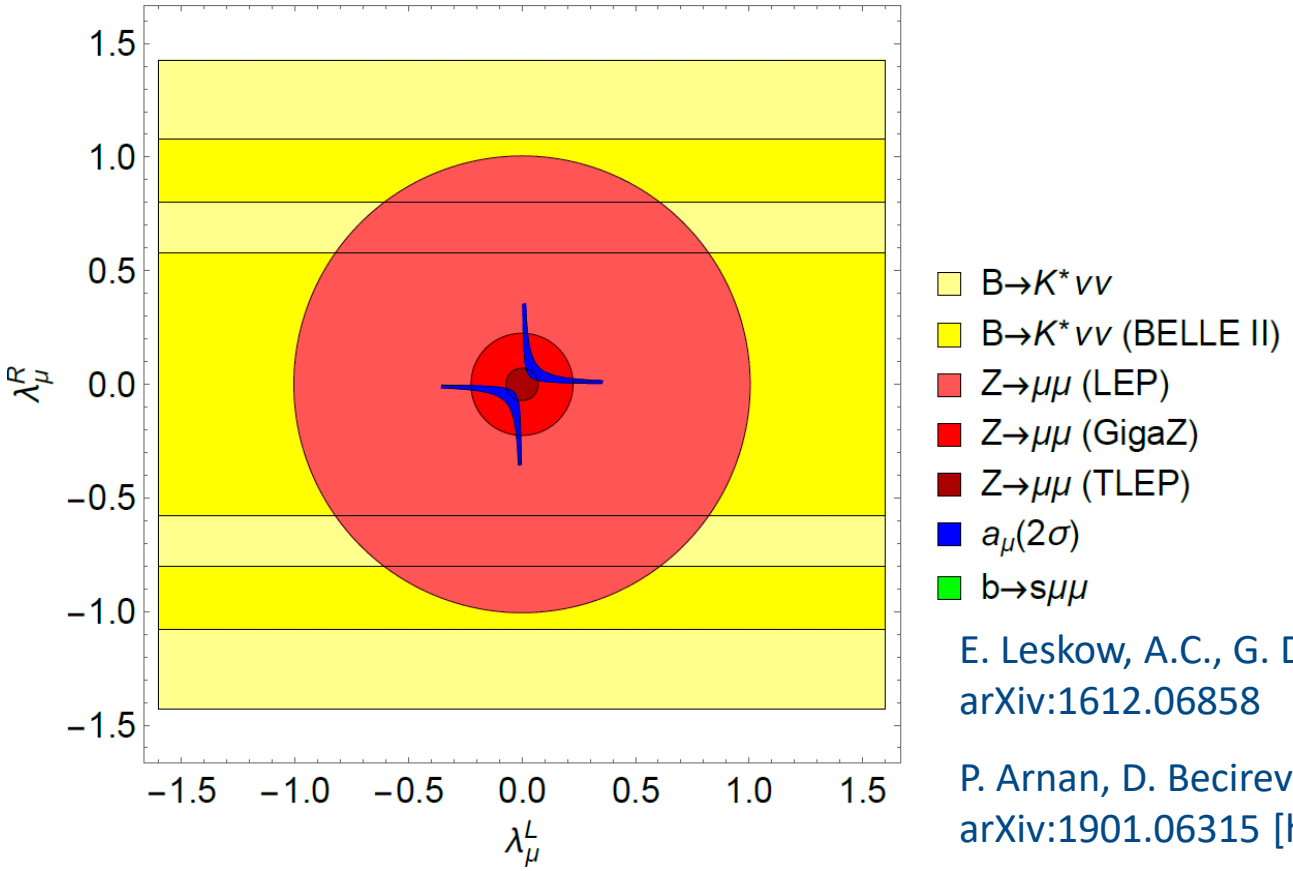


e.g. D. Stockinger, hep-ph/0609168

tan(ß) enhanced slepton and sneutrino loops

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

P. Arnan, D. Becirevic, F. Mescia, O. Sumensari,
arXiv:1901.06315 [hep-ph]

Z→μμ at future colliders

2HDMs

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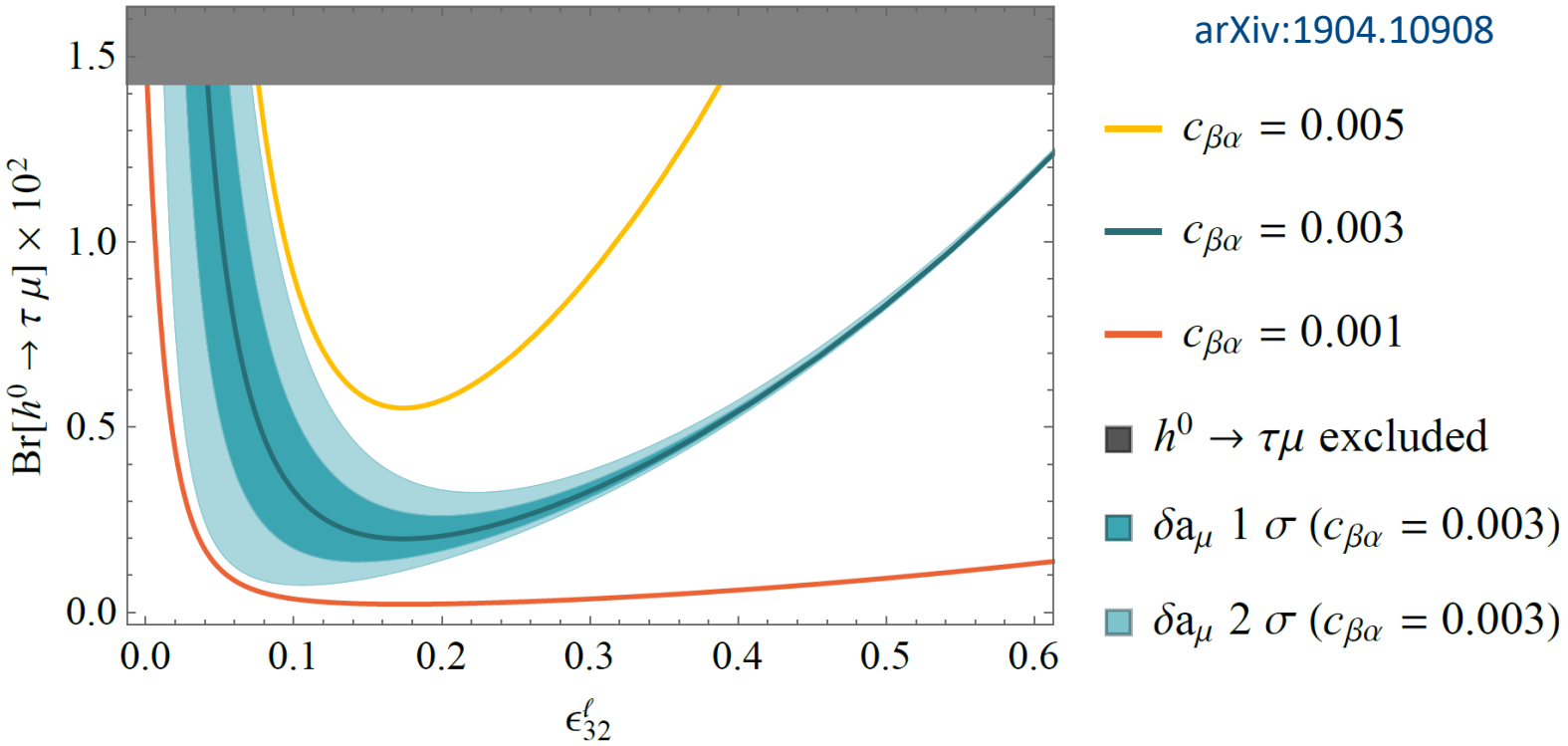
- Chirally enhancement of m_τ/m_μ

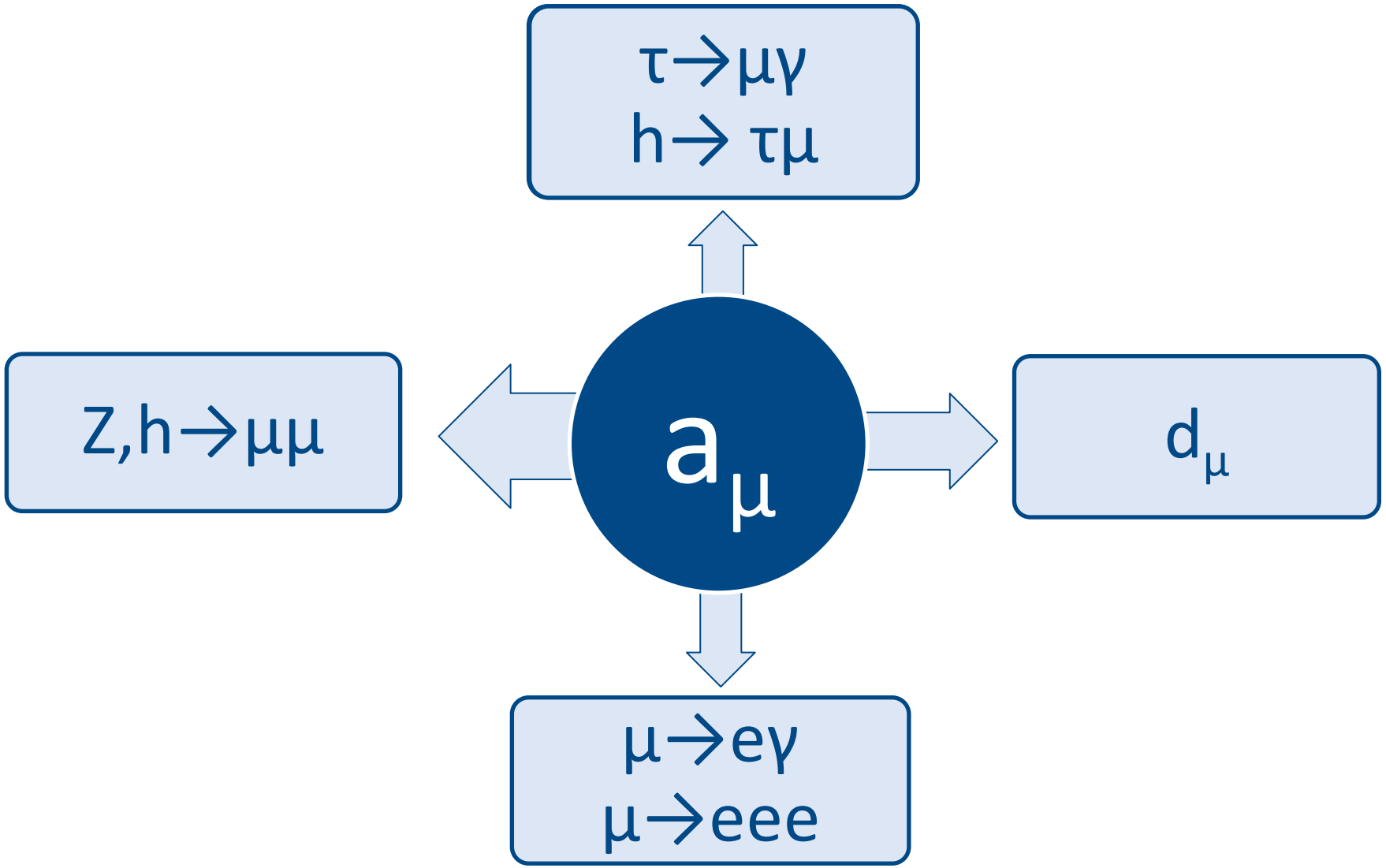
AC, D. Müller, C. Wiegand
arXiv:1903.10440

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



Unavoidable constraints from h→τμ

Future Implications of a_μ



Correlations with the AMM of the electron

AC, M. Hoferichter, P. Schmidt-Wellenburg, arXiv:1807.11484

See also

H. Davoudiasl, W. J. Marciano, arXiv:1806.10252

Jia Liu, Carlos E.M. Wagner, Xiao-Ping Wang, arXiv:1810.11028

…

Electron AMM

- 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

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

2.5 σ deviation with opposite sign than a_μ

Common explanation of a_μ and a_e

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

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

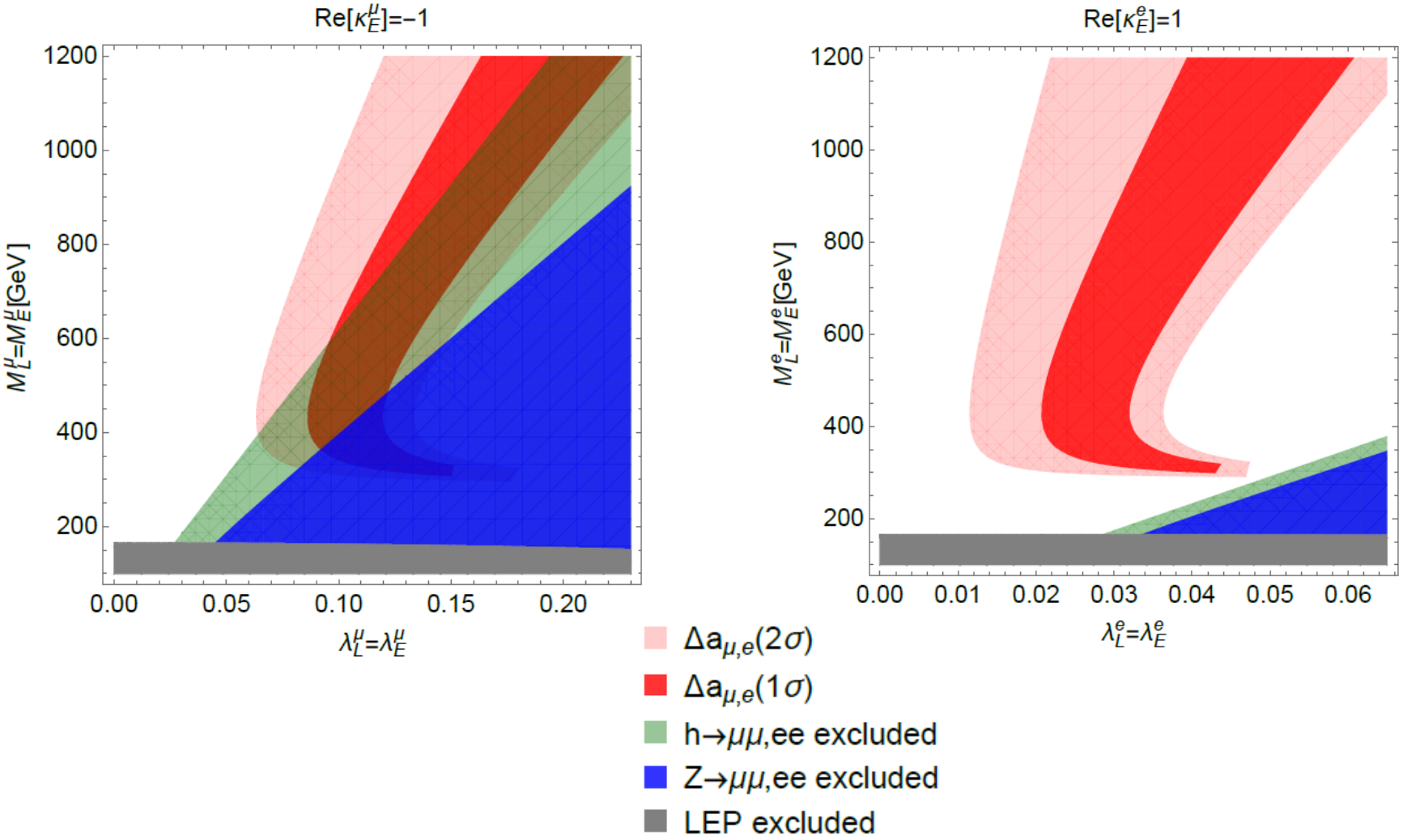
  ⇒ generic flavour structure
- New physics with common couplings to μ and e

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

8 orders of magnitude too large

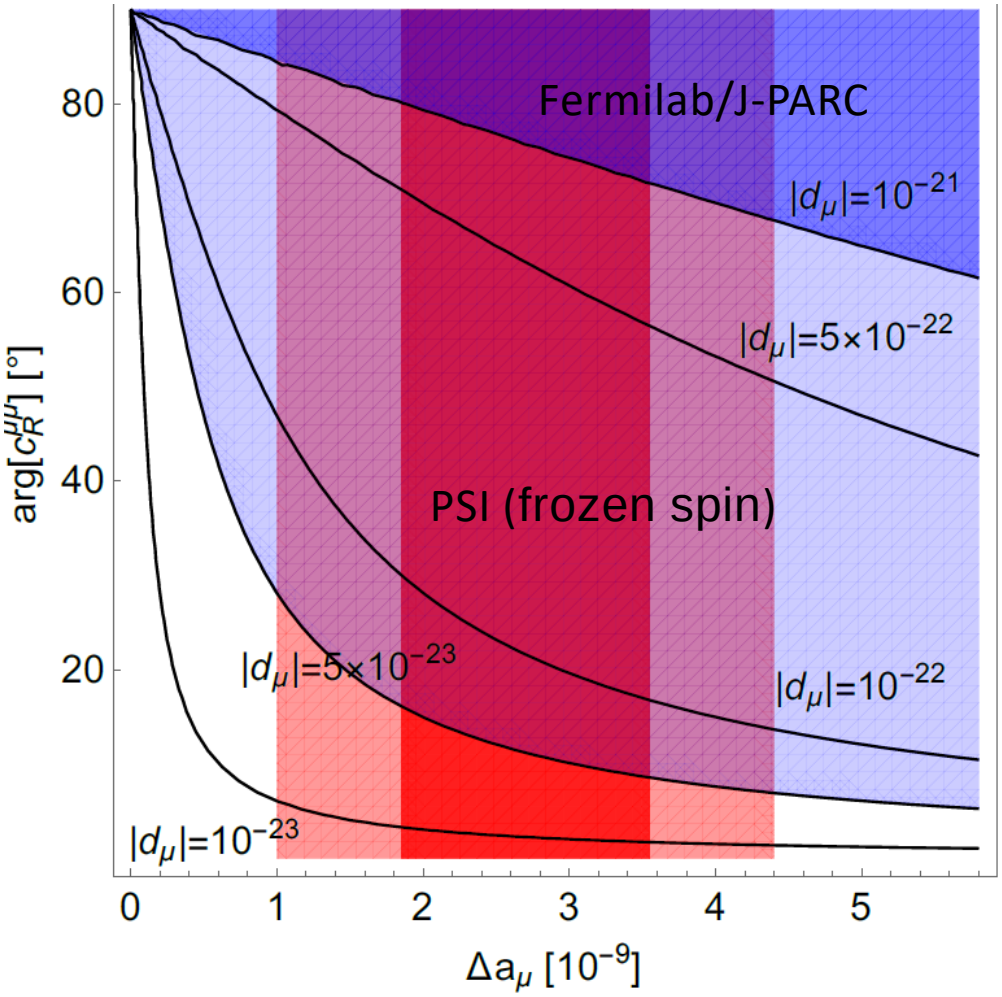
Muon and electron sector must be decoupled

Model with new vector-like leptons



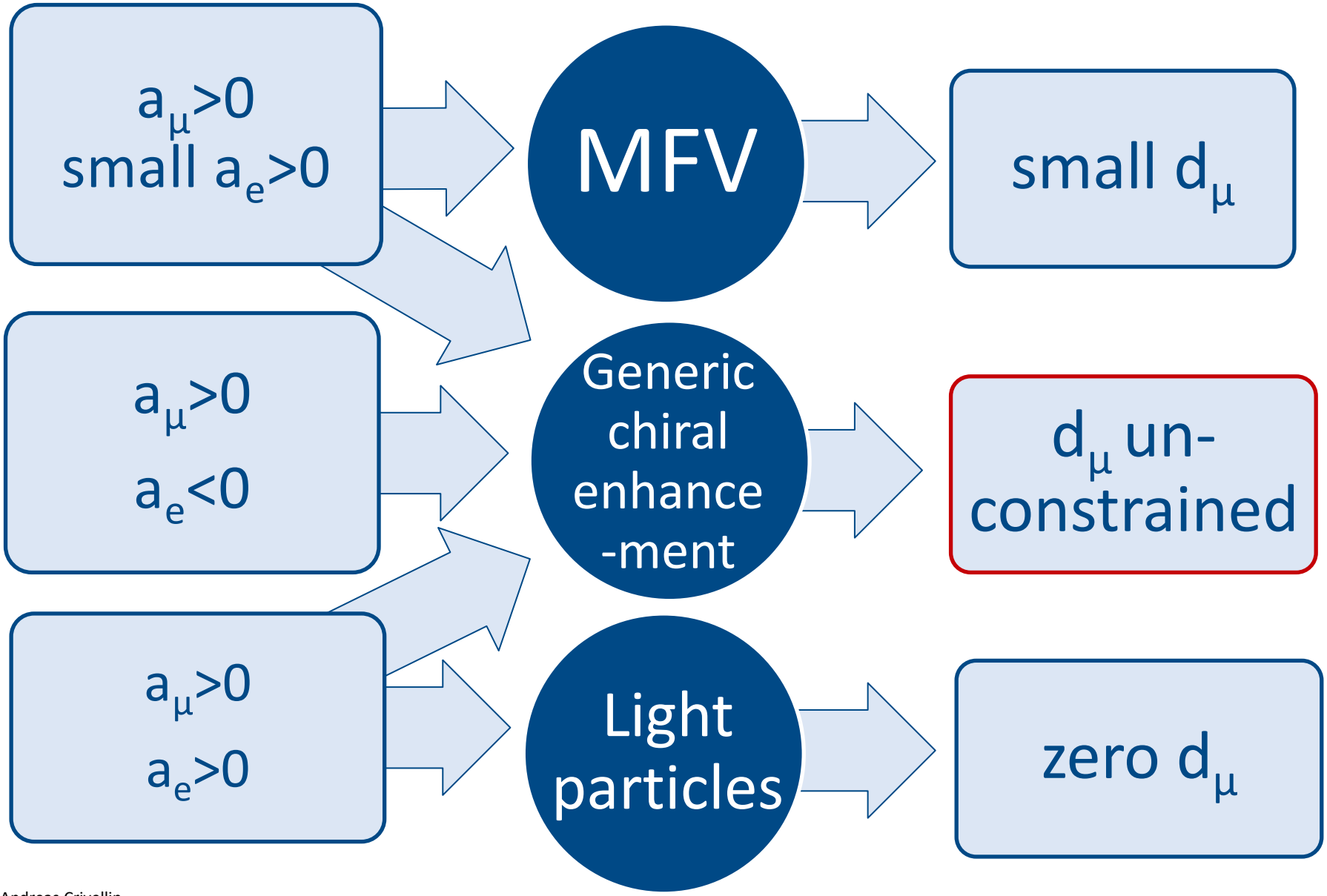
Works for a_e but tension with a_μ

Future experimental sensitivity

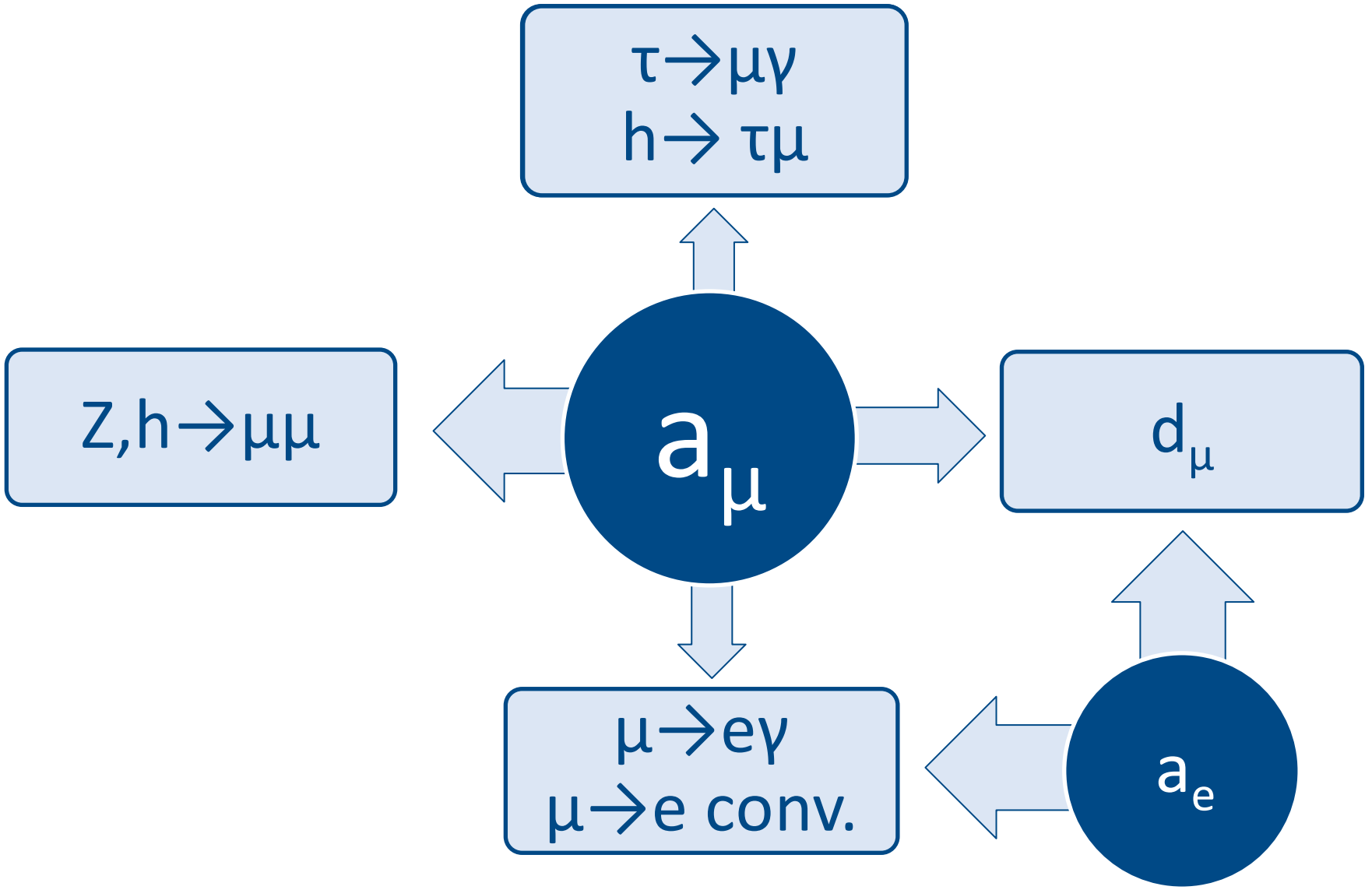


Dedicated experiment needed?

Implications for Muon EDM

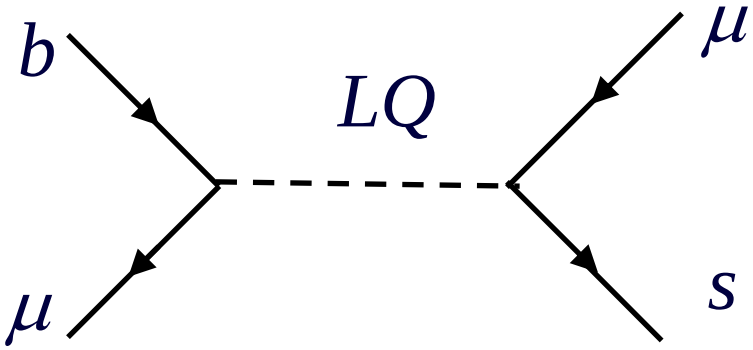


Future Implications of a_μ



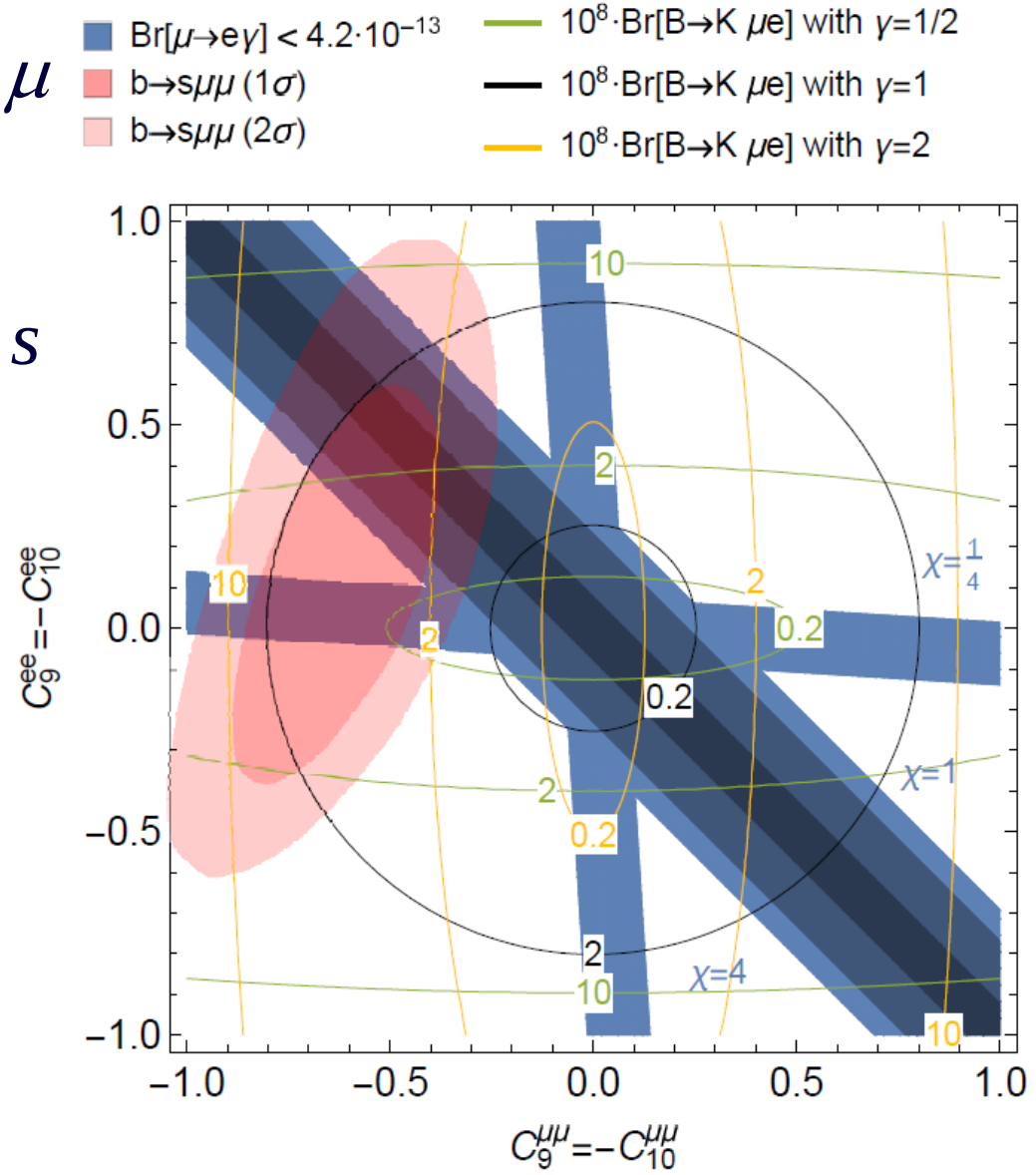
Including LFVU in $b \to s \ell\ell$

b→sμ⁺μ⁻: Leptoquarks

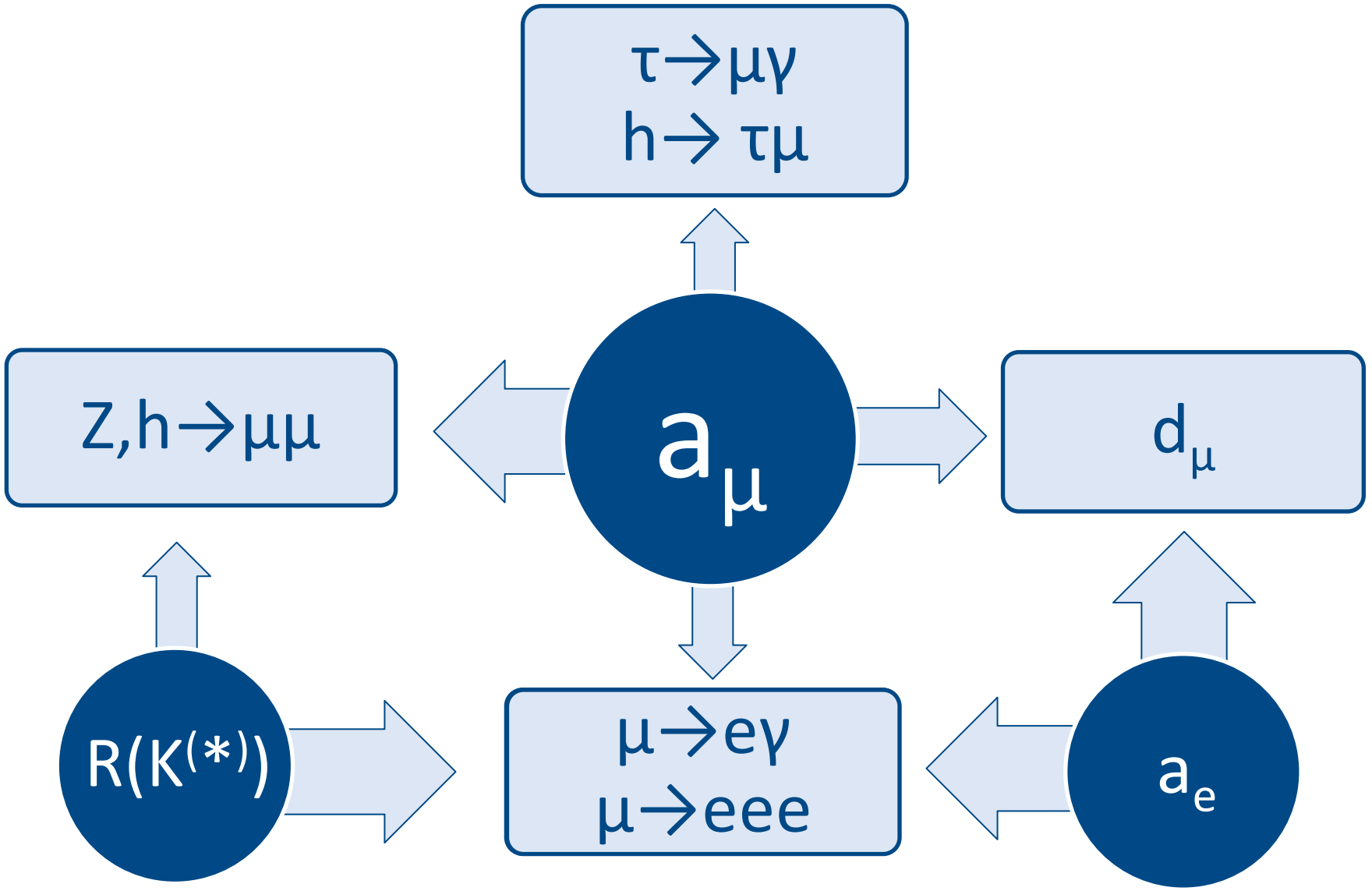


- Small effect in B_s mixing

Lepton flavour violation

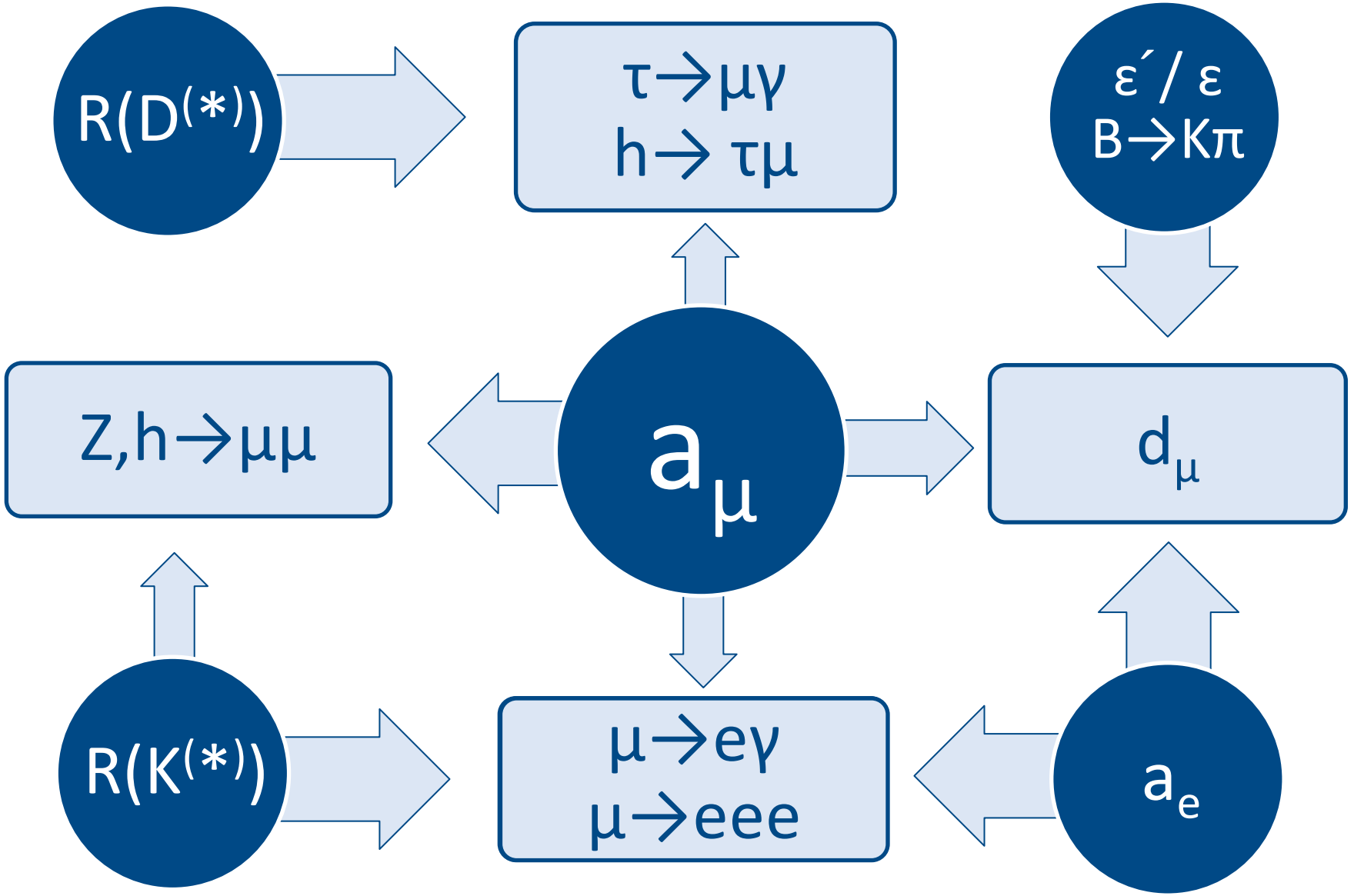


Future directions



Many more such possible correlations...

Future directions



Backup

Models for a common explanation

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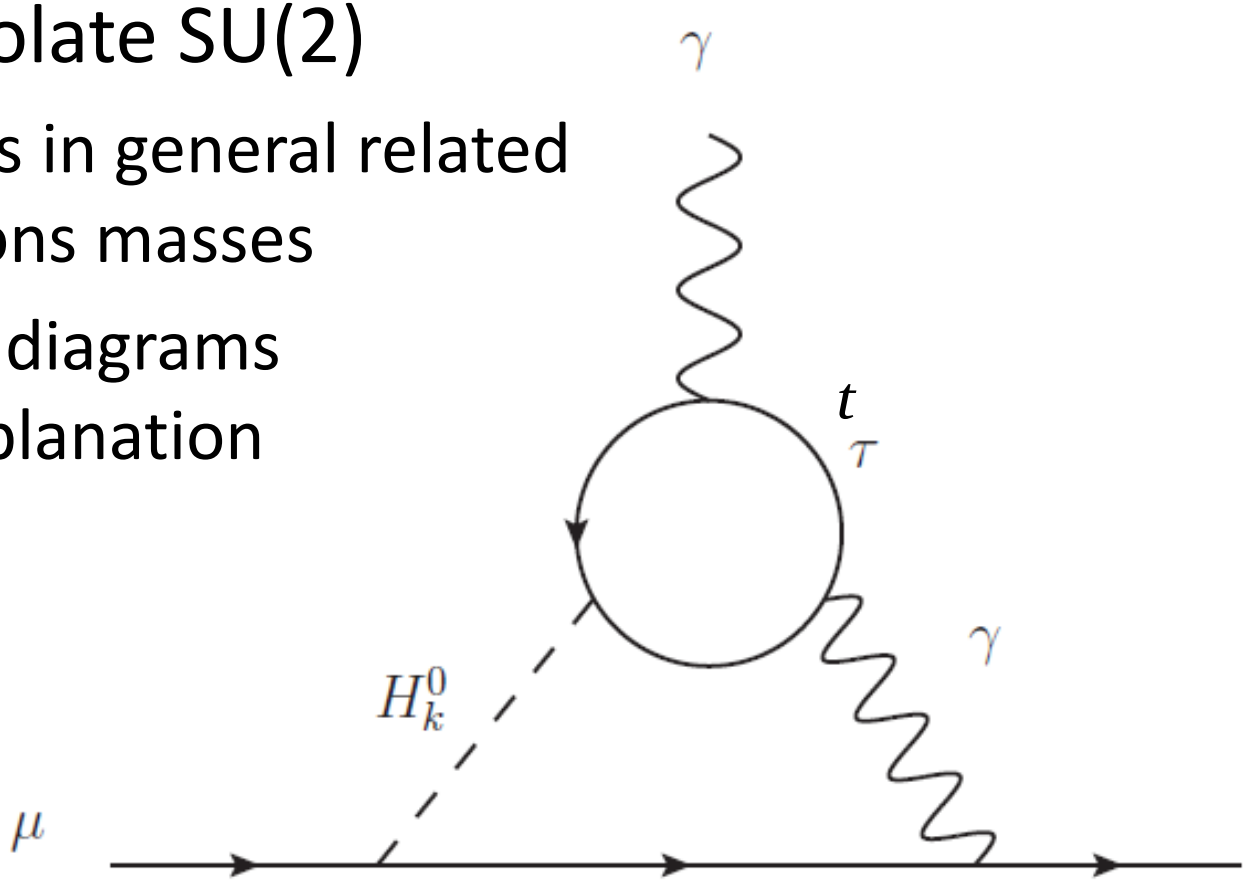
- MSSM
  - Constrained MFV does not work
  - With generic A-terms has problem with vacuum stability
  - With large tan(ß) and flavour violation
- 2HDMs & LQs: Problems with $\mu \to e\gamma$
- Extra dimensions
  - Can only explain the muon or the electron AMM because of $\mu \to e\gamma$

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

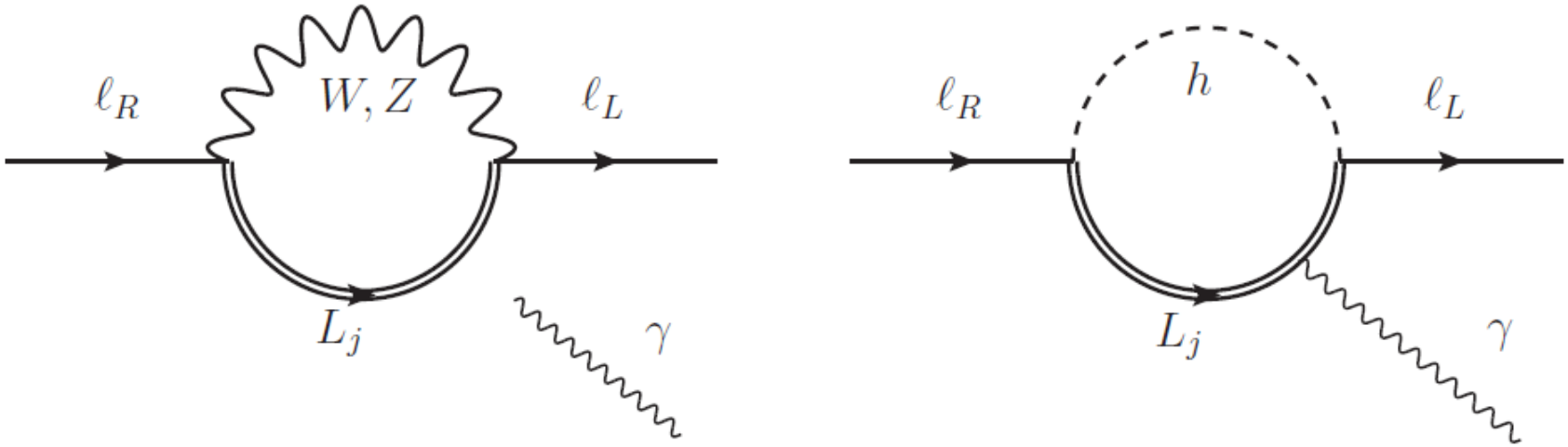
Modifications to the model

- Add neutral scalar
  - Effect in a_μ possible without affecting $h \to \mu\mu$
- Impose abelian flavour symmetry (e.g. $L_\mu - L_\tau$) 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 $L_\mu - L_\tau$ 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 $v\kappa_{L,R}/m_\mu$

Limits on the Muon EDM

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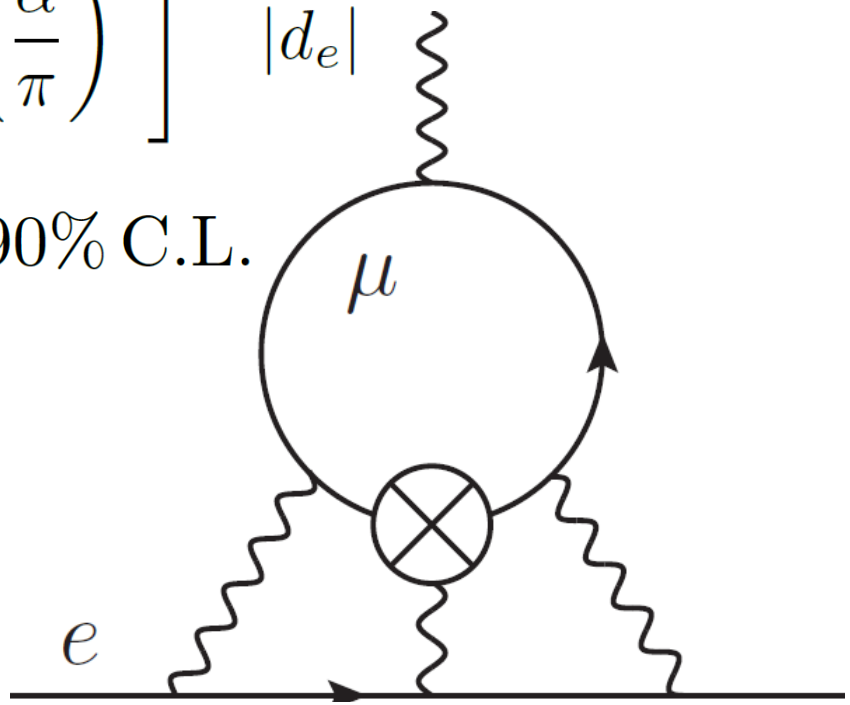
- MFV:
- Contribution only starts at the 3-loop level

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

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



- Direct limit

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

Improvement of direct limit important

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 $h \to \mu\mu$