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# Anomalous Magnetic Moments in and Beyond the Standard Model

**Pisa (remote), 20.04.2020**

# Outline

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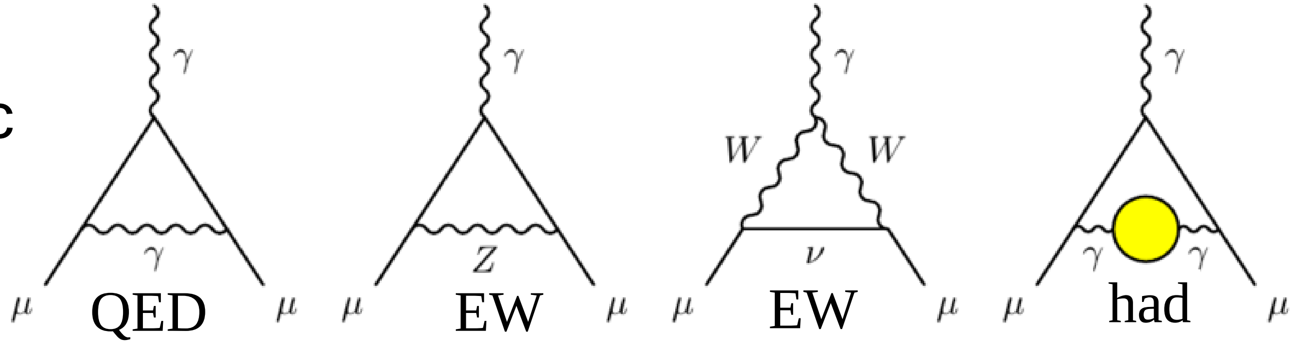
- Status of the Anomalous Magnetic Moment of the Muon
- Hadronic Vacuum polarization and Electro Weak Fit
- Explaining the anomalous magnetic moment of the muon with new physics
- $a_\mu$ and consequences for future measurements
- Correlations with the electron AMM and implications for the muon EDM
- Further Flavour anomalies and future prospects

# Muon Anomalous Magnetic Moment

- Single measurement from BNL

$$a_\mu \approx 116592089(63) \times 10^{-11}$$

- New Fermilab experiment aims at an reduction of the error by a factor 4
- Planned J-PARK experiment with completely different systematics
- SM prediction had three components
  - QED
  - Hadronic
  - EW



# SM Theory Prediction: EW and QED

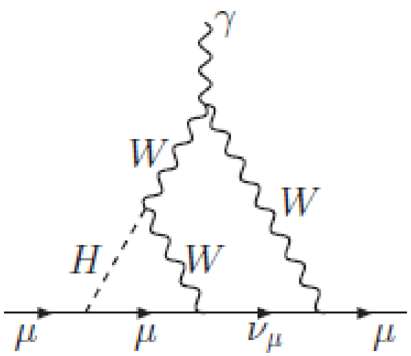
- QED 5-loop contribution T. Aoyama, T. Kinoshita, M. Nio, PRD, 2018

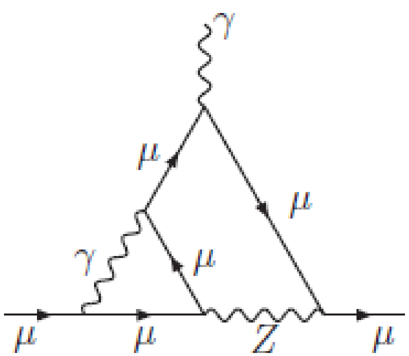
$$a_\mu(QED) \approx 116584718.951(0.080) \times 10^{-11}$$

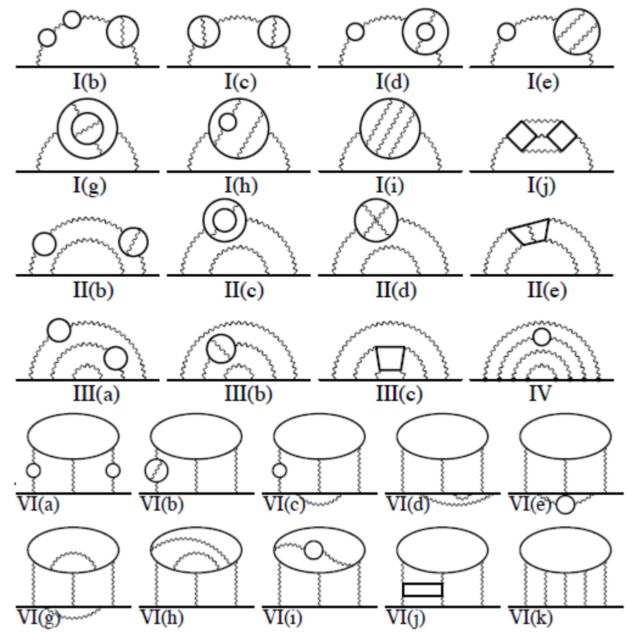
- EW 2-loop effect

C. Gnendiger, D. Stöckinger, H. Stöckinger-Kim, PRD (2013)

$$a_\mu(EW) \approx 153.6(1.0) \times 10^{-11}$$



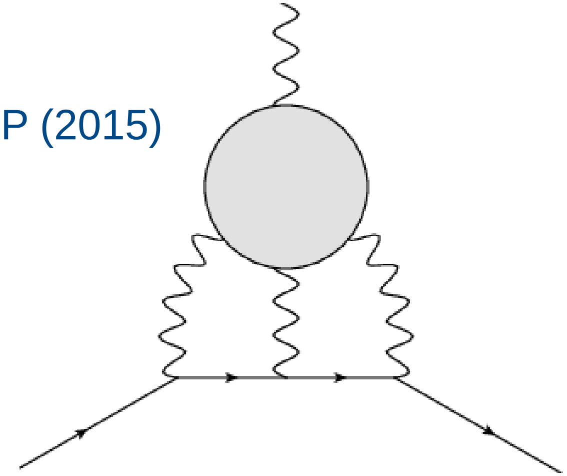

**QED and EW well under control**

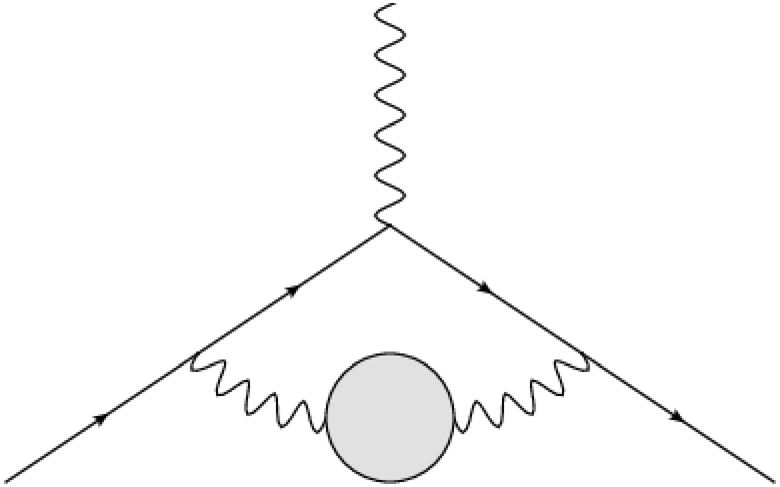
# SM Theory: Hadronic Effects

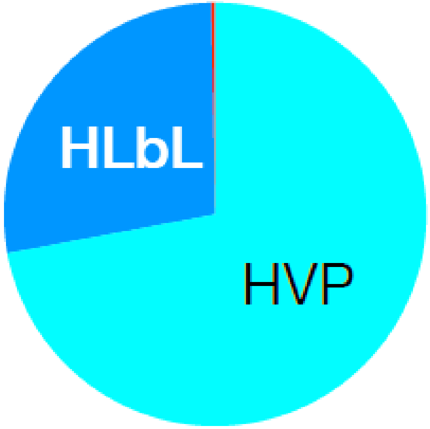
- Hadronic light-by-light scattering

  G. Colangelo, M. Hoferichter, M. Procura, P. Stoffer, JHEP (2015)

  - Dispersive approach works well
- Hadronic vacuum polarization






**Leading uncertainties from hadronic effects**

# Hadronic Vacuum Polarization

- Dispersive approach

$$a_\mu^{\mathrm{HVP}} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \int_{s_{\mathrm{thr}}}^{\infty} ds \frac{\hat{K}(s)}{s^2} R_{\mathrm{had}}(s), \quad s_{\mathrm{thr}} = m_{\pi^0}^2$$

$$R_{\mathrm{had}}(s) = \frac{3s}{4\pi\alpha^2}\sigma(e^+e^- \to \mathrm{hadrons})$$

M. Davier, A. Hoecker, B. Malaescu, Z. Zhang, EPJC (2020)
A. Keshavarzi, D. Nomura, T. Teubner, PRD (2020)

$$\Delta\alpha_{\mathrm{had}}^{(5)}\Big|_{e^+e^-} = 276.1(1.1)\times 10^{-4}$$

$$\Delta\alpha_{\mathrm{had}}^{(5)}(M_Z^2) = \frac{\alpha M_Z^2}{3\pi}\int_{s_{\mathrm{thr}}}^{\infty} ds \frac{R_{\mathrm{had}}(s)}{s(M_Z^2 - s)}$$

- New BMWc lattice result

$$\Delta\alpha_{\mathrm{had}}^{(5)}\Big|_{BMWc}^{\le M_Z} = 283.8(1.3)\times 10^{-4},$$

$$\Delta\alpha_{\mathrm{had}}^{(5)}\Big|_{BMWc}^{\le 11.2 GeV} = 280.3(1.3)\times 10^{-4},$$

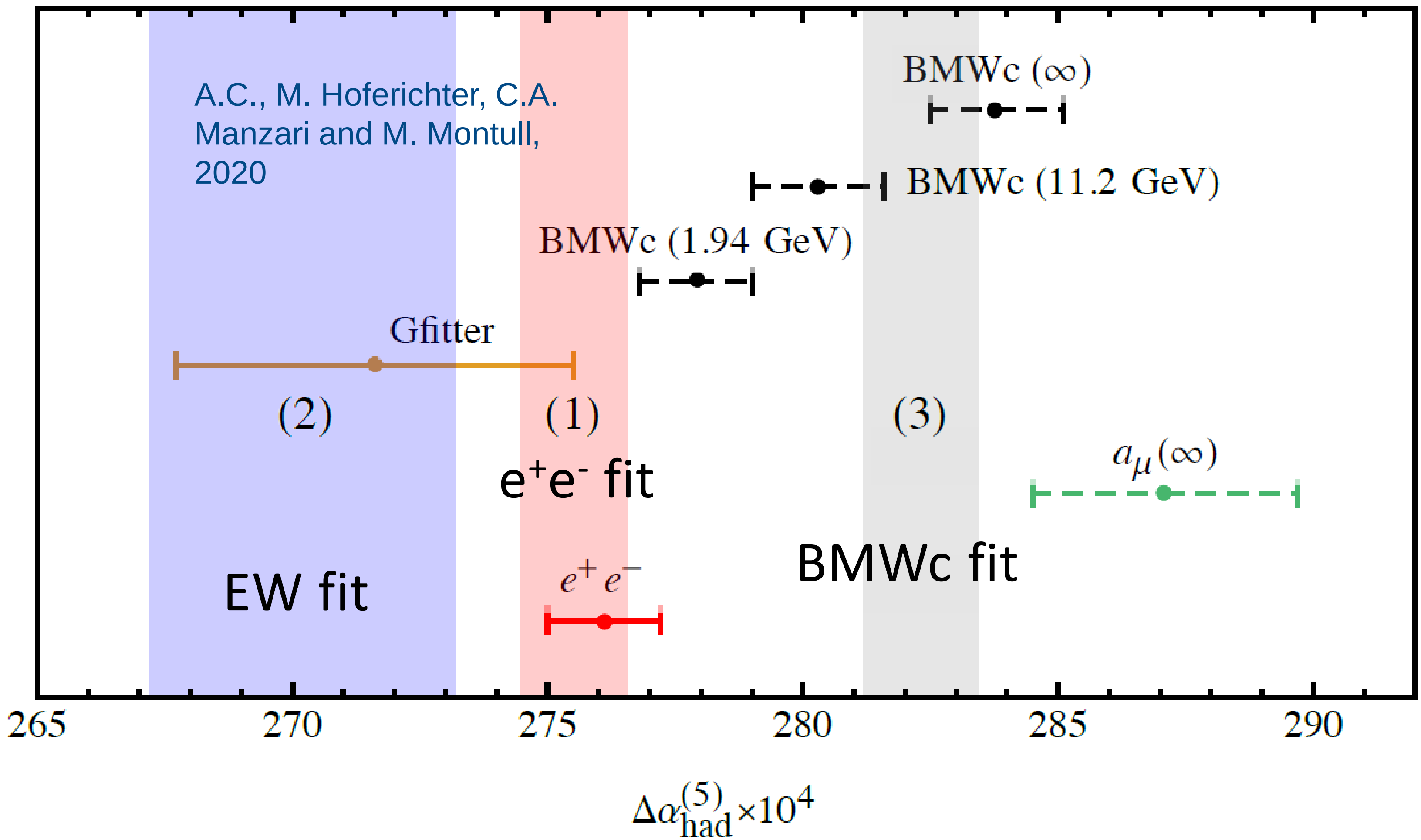
$$\Delta\alpha_{\mathrm{had}}^{(5)}\Big|_{BMWc}^{\le 1.94} = 277.9(1.1)\times 10^{-4},$$

S. Borsanyi et al., [arXiv:2002.12347 [hep-lat]].

(energy dependence not know)

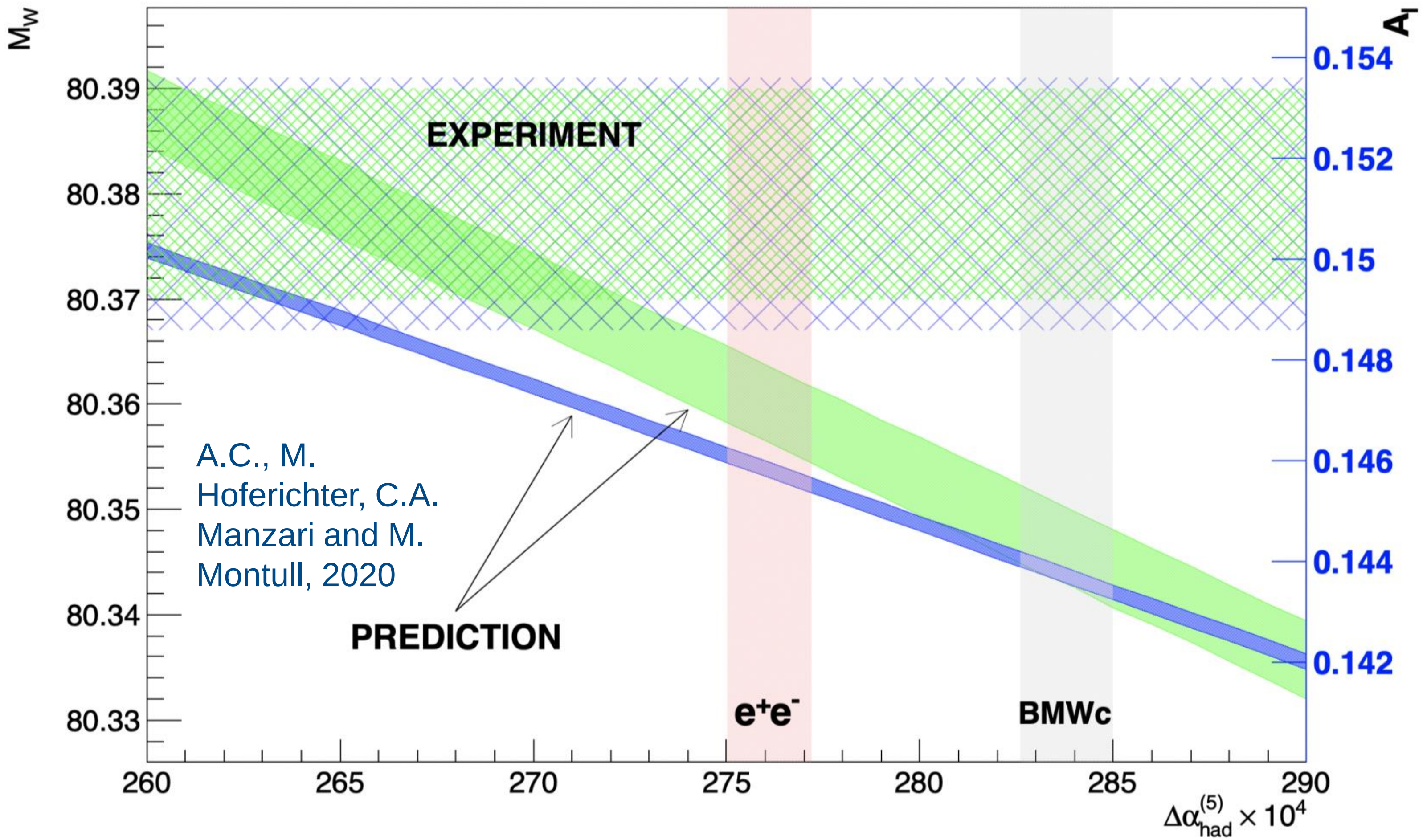
**BMWc result in tension with $e^+e^-$; would solve g-2**

# HVP enters EW fit




**BMWc result leads to significant tension**

# Tensions in the EW fit




**Tensions call for (different) NP**

# Explaining the AMM of the muon

# Dipoles in the EFT

- Effective Hamiltonian

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

- Anomalous magnetic moment

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

- Electric Dipole moment

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

- Radiative Lepton decays

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

**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)

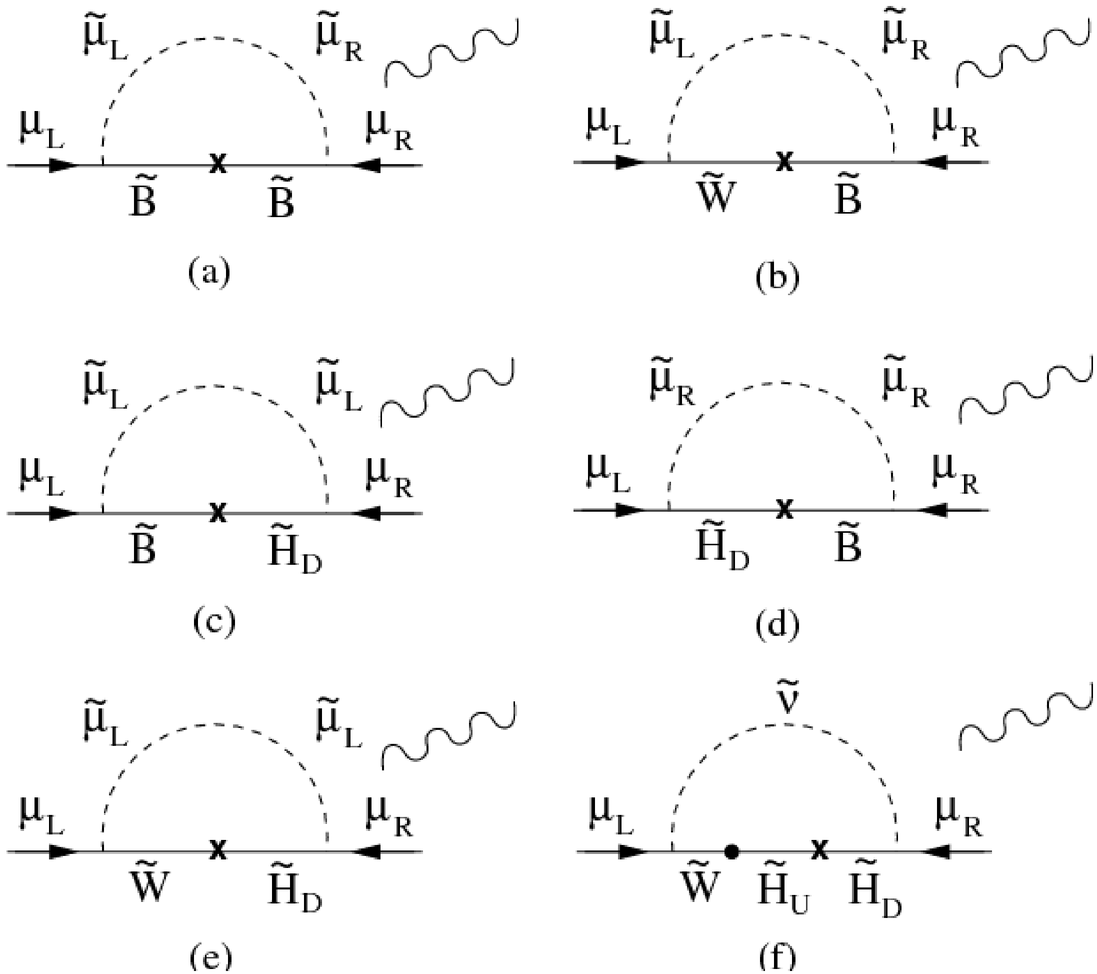
Huge literature

- 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**

# $a_\mu$: MSSM



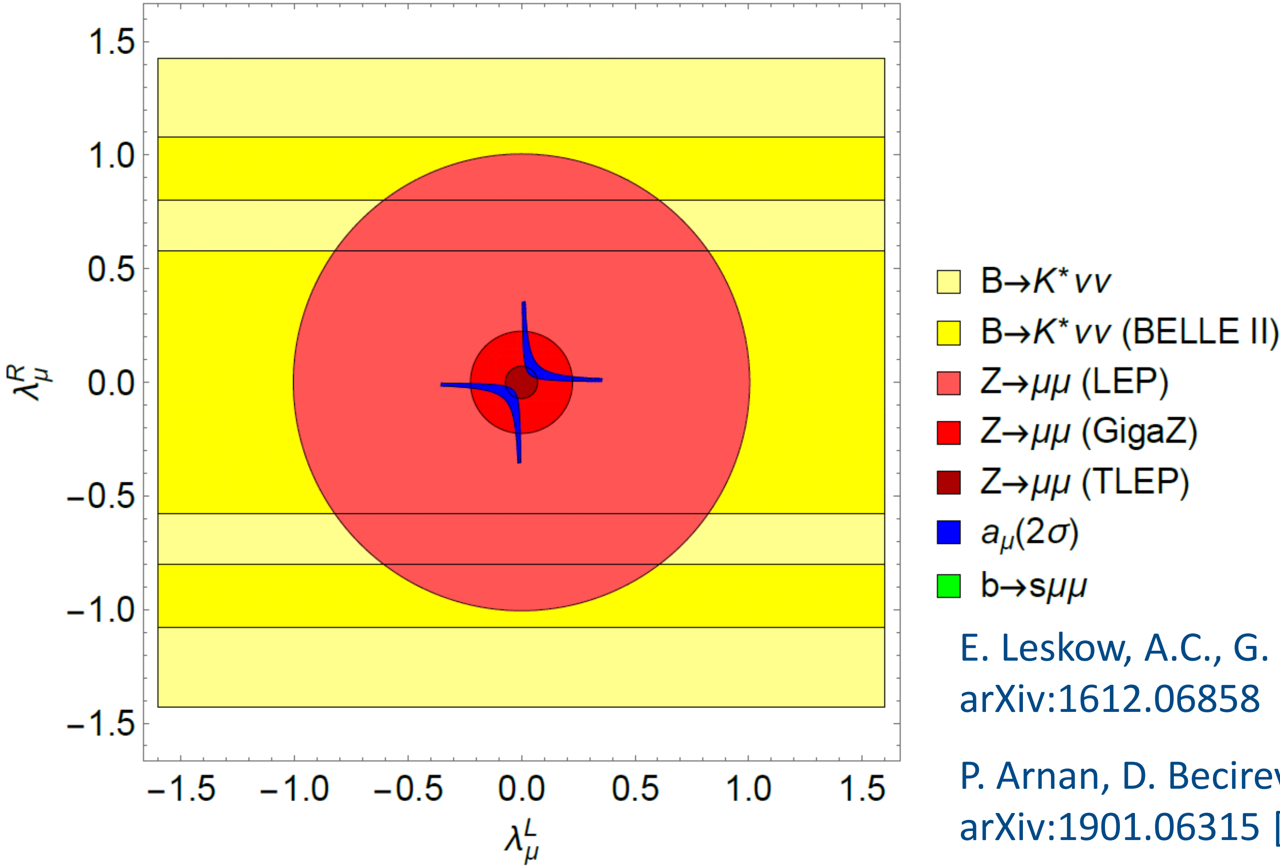



e.g. D. Stockinger, hep-ph/0609168

**tan(ß) enhanced slepton and sneutrino loops**

# Leptoquarks in $a_\mu$

- 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]

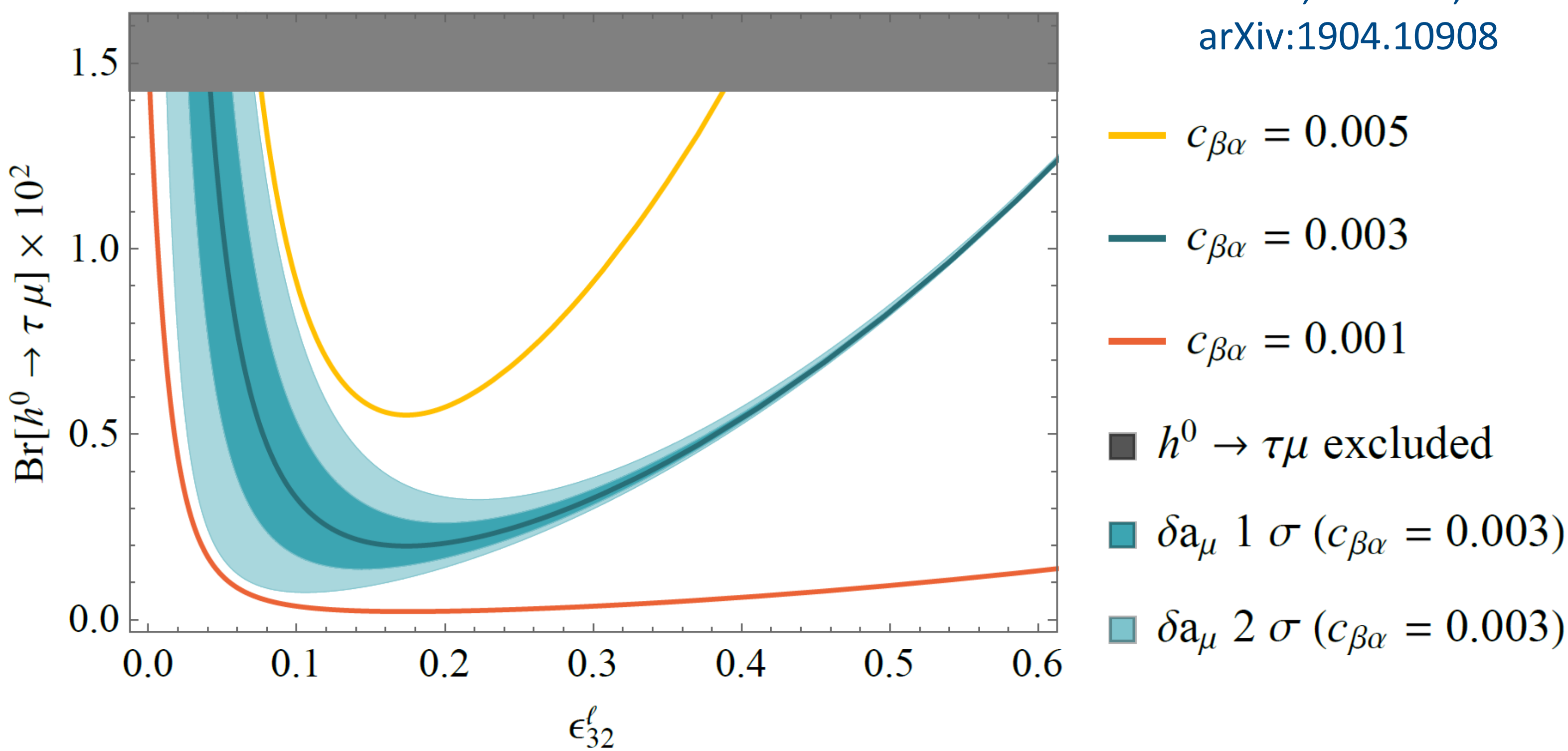
**Z→μμ at future colliders**

# 2HDMs

- Chirally enhancement of $m_\tau/m_\mu$

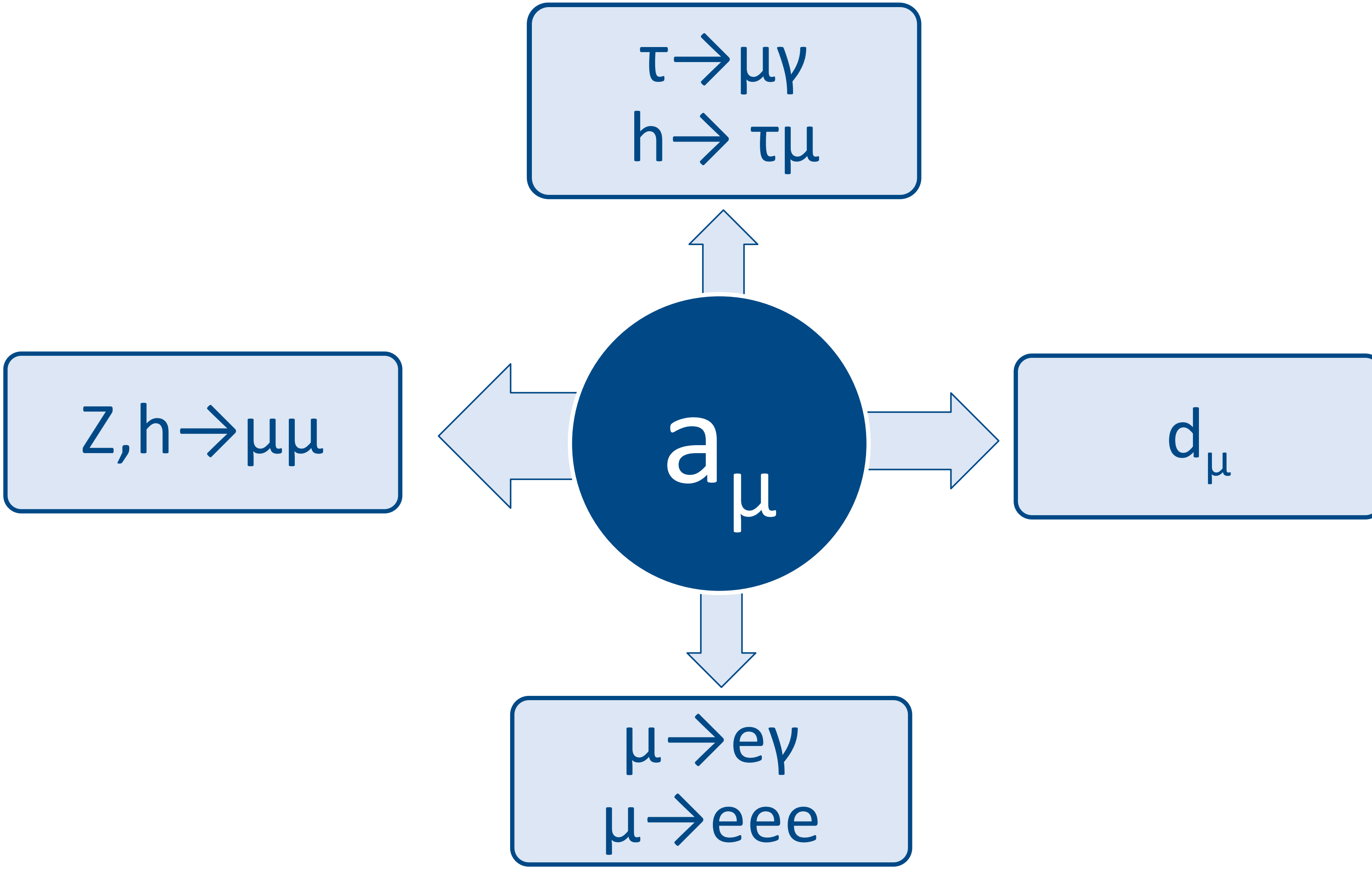
AC, D. Müller, C. Wiegand
arXiv:1903.10440

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




**Unavoidable constraints from h→τμ**

# Future Implications of $a_\mu$



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# 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

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- 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

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

- 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 $a_\mu$**

# Common explanation of $a_\mu$ and $a_e$

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- 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

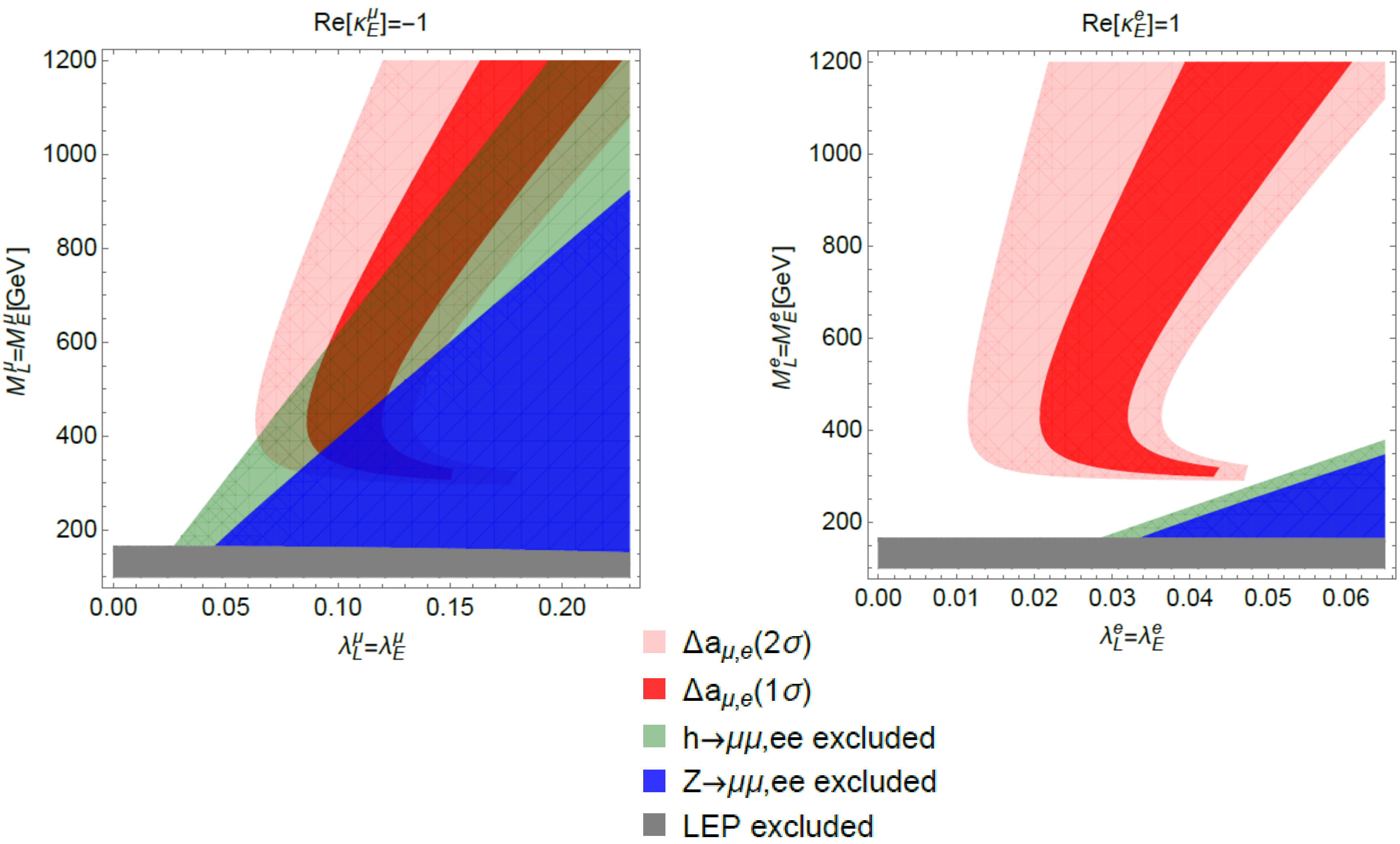
- New physics with common couplings to μ and e

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

8 orders of magnitude too large

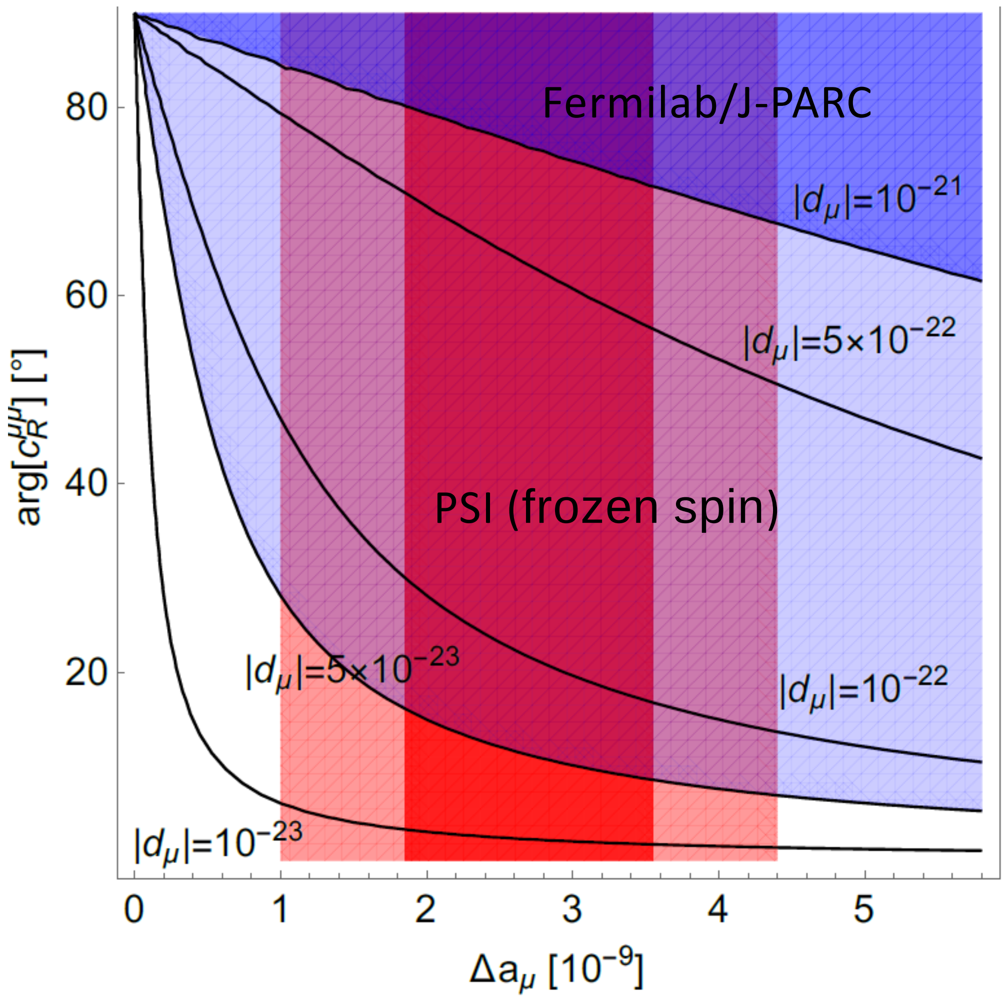
**Muon and electron sector must be decoupled**

# Model with new vector-like leptons



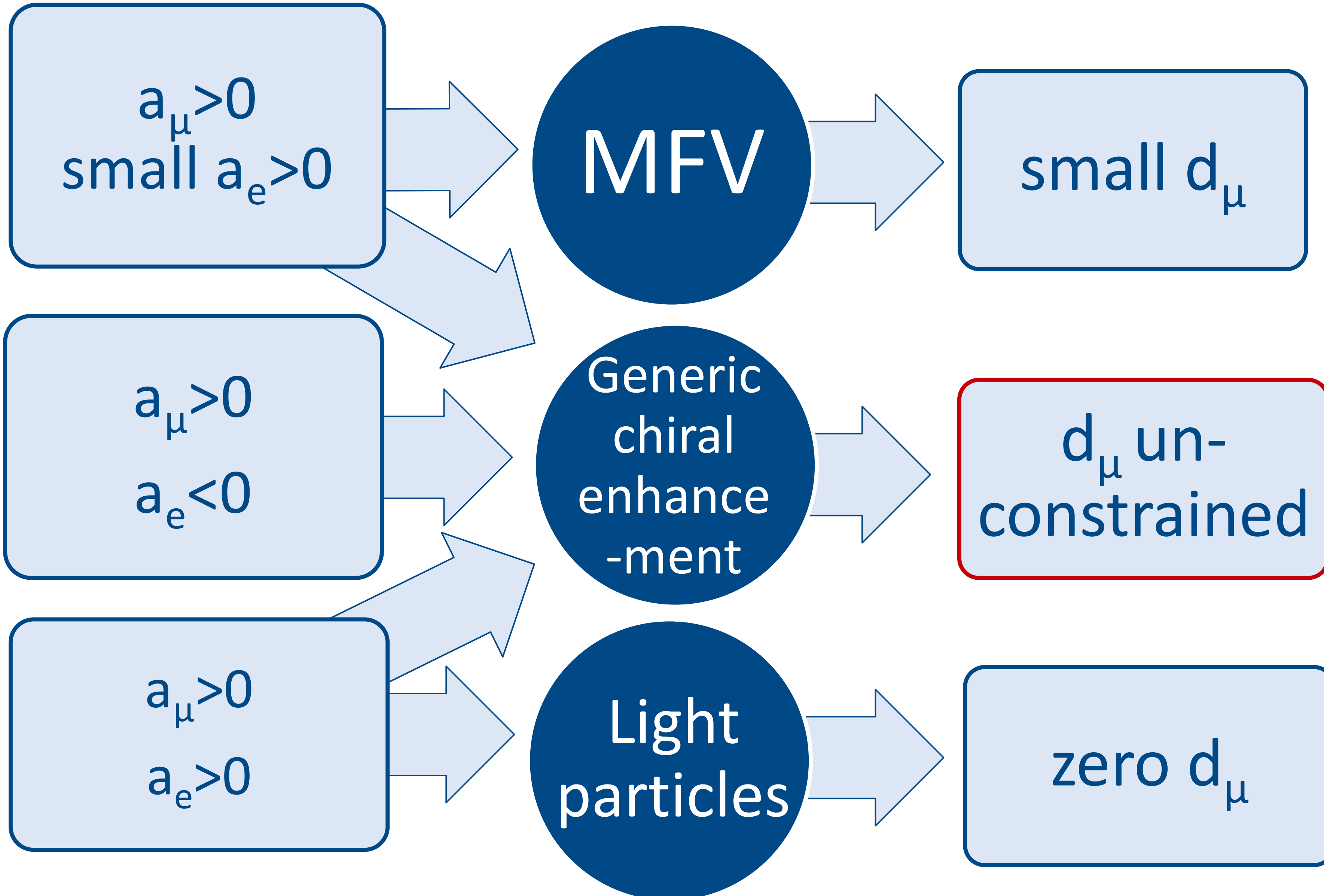

**Works for $a_e$ but tension with $a_\mu$**

# Future experimental sensitivity

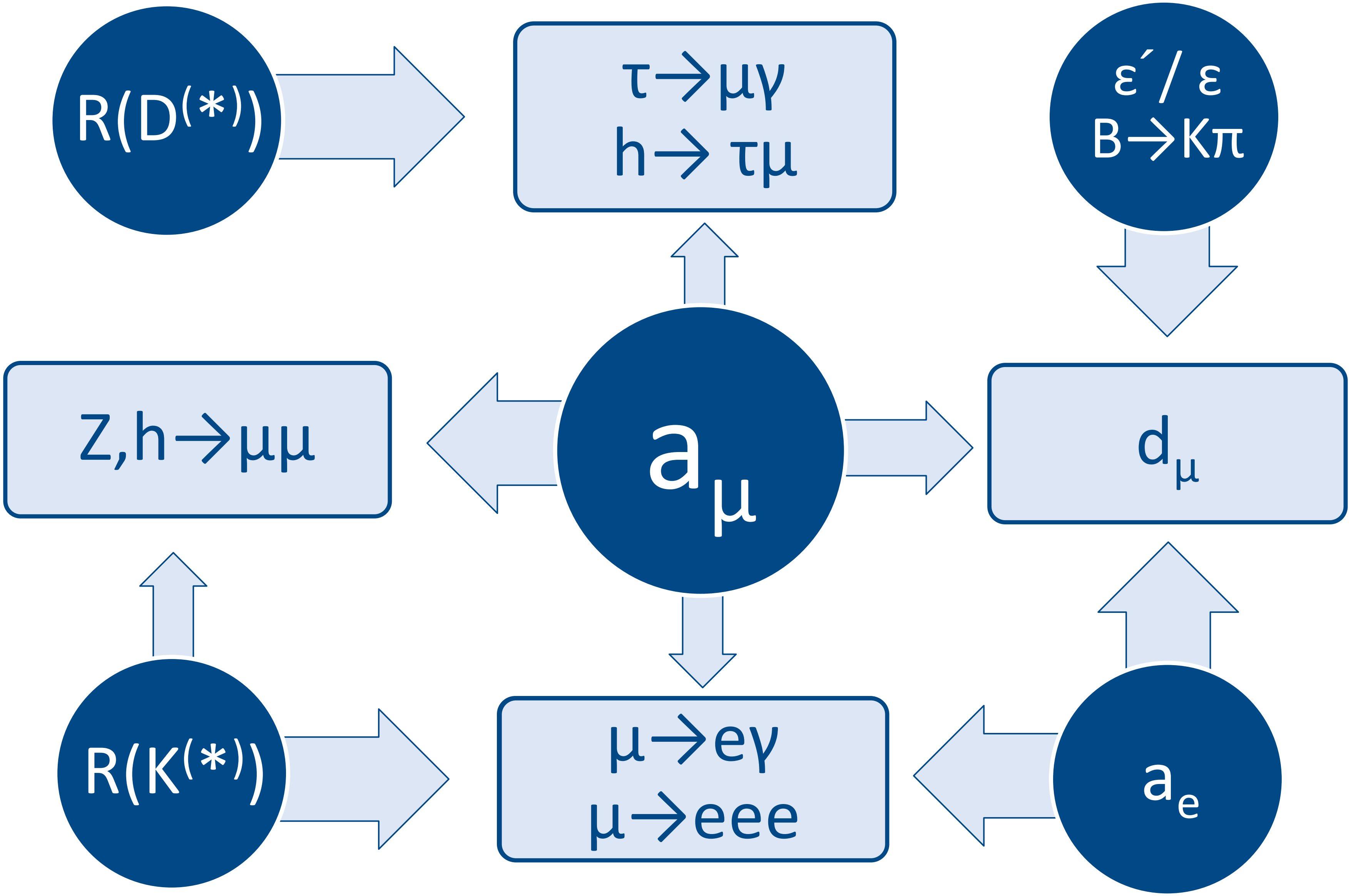



**Dedicated experiment needed?**

# Implications for Muon EDM



# Future directions



# Backup

# $a_\mu$ and further hints for New Physics

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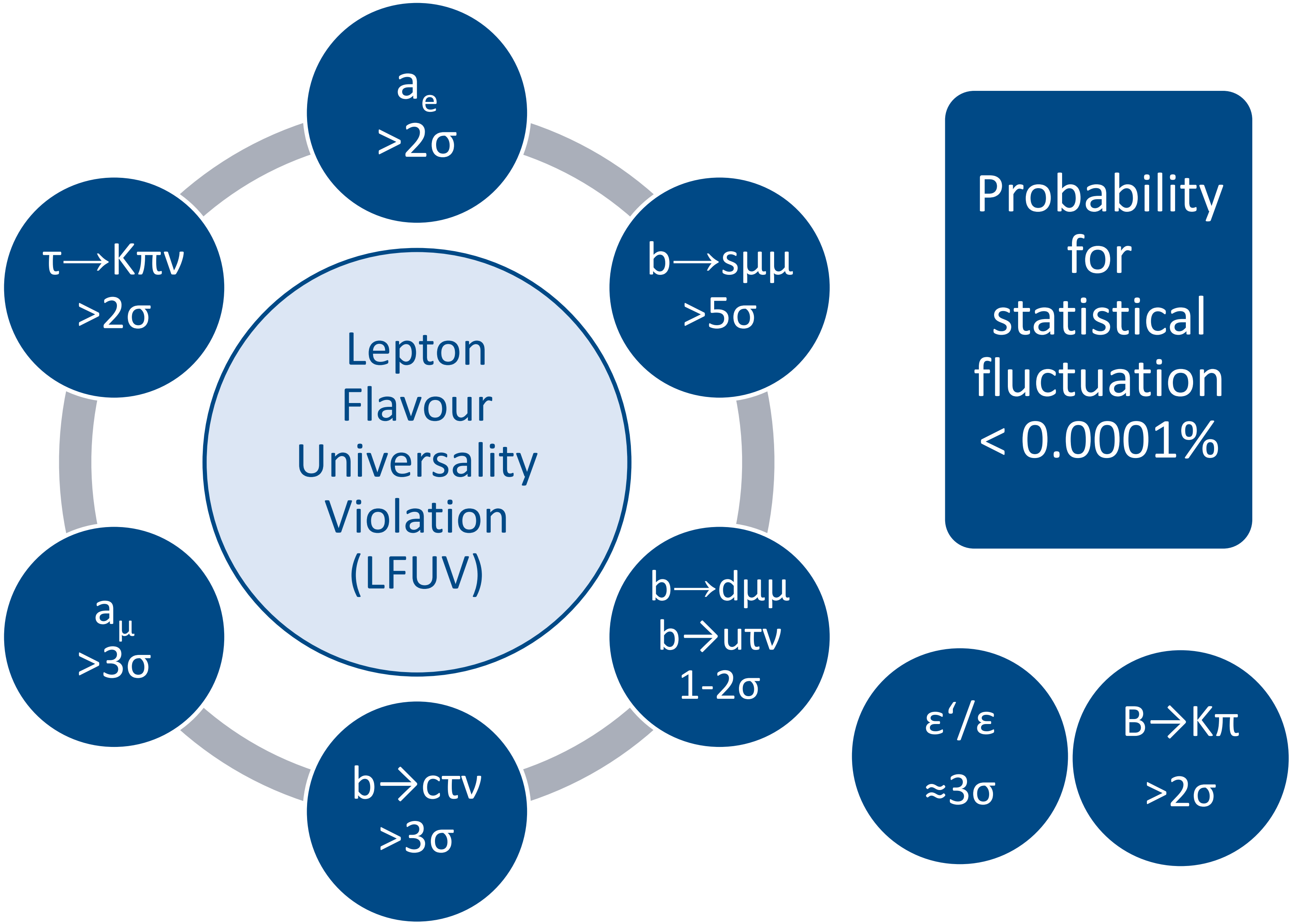

| Observable | Reference | Measurement | Posterior (1) | Pull (1) | Posterior (2) | Pull (2) | Posterior (3) | Pull (3) |
|---|---|---|---|---|---|---|---|---|
| $\alpha_s(M_Z)$ | [1] | 0.1181(11) | 0.1181(10) | 0.003 | 0.1181(10) | 0.004 | 0.1181(10) | 0.02 |
| $M_Z$ [GeV] | [2] | 91.1875(21) | 91.1883(20) | −0.27 | 91.1877(21) | −0.05 | 91.1891(20) | −0.55 |
| $m_t$ [GeV] | [3–5] | 172.80(40) | 172.95(39) | −0.27 | 172.85(39) | −0.09 | 173.09(39) | 0.51 |
| $M_H$ [GeV] | [6, 7] | 125.16(13) | 125.16(13) | 0.01 | 125.16(13) | 0.01 | 125.16(13) | 0.02 |
| $M_W$ [GeV] | [1] | 80.379(12) | 80.363(4) | 1.25 | 80.372(6) | 0.56 | 80.353(4) | 2.10 |
| $\Gamma_W$ [GeV] | [1] | 2.085(42) | 2.088(1) | −0.09 | 2.089(1) | −0.10 | 2.088(1) | −0.07 |
| $\mathrm{BR}(W \to \ell\nu)$ | [1] | 0.1086(9) | 0.10838(2) | 0.25 | 0.10838(1) | 0.25 | 0.10838(1) | 0.25 |
| $\mathrm{BR}(W \to \mathrm{had})$ | [1] | 0.6741(27) | 0.6749(1) | −0.28 | 0.6749(1) | −0.28 | 0.6749(1) | −0.28 |
| $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}(Q_{\mathrm{FB}}^{\mathrm{had}})$ | [2] | 0.2324(12) | 0.2316(4) | 0.63 | 0.2315(1) | 0.77 | 0.2319(1) | 0.44 |
| $\sin^2\theta_{\mathrm{eff(Had.coll.)}}^{\mathrm{lept}}$ | [8, 9] | 0.23143(27) | 0.2316(4) | −0.78 | 0.2315(1) | −0.14 | 0.2319(1) | −1.62 |
| $P_\tau^{\mathrm{pol}}$ | [2] | 0.1465(33) | 0.1461(3) | 0.13 | 0.1475(8) | −0.28 | 0.1443(3) | 0.68 |
| $A_\ell$ | [2] | 0.1513(21) | 0.1461(3) | 2.47 | 0.1475(8) | 1.71 | 0.1443(3) | 3.31 |
| $\Gamma_Z$ [GeV] | [2] | 2.4952(23) | 2.4947(6) | 0.22 | 2.4951(6) | 0.05 | 2.4942(6) | 0.43 |
| $\sigma_h^0$ [nb] | [2] | 41.541(37) | 41.485(6) | 1.50 | 41.485(6) | 1.51 | 41.485(6) | 1.50 |
| $R_\ell^0$ | [2] | 20.767(35) | 20.747(7) | 0.79 | 20.750(7) | 0.66 | 20.743(7) | 0.95 |
| $A_{\mathrm{FB}}^{0,\ell}$ | [2] | 0.0171(10) | 0.0160(1) | 1.10 | 0.0163(2) | 0.78 | 0.0156(1) | 1.49 |
| $R_b^0$ | [2] | 0.21629(66) | 0.21582(1) | 0.71 | 0.21582(1) | 0.71 | 0.21583(1) | 0.70 |
| $R_c^0$ | [2] | 0.1721(30) | 0.17219(2) | −0.03 | 0.17220(2) | −0.03 | 0.17218(2) | −0.03 |
| $A_{\mathrm{FB}}^{0,b}$ | [2] | 0.0992(16) | 0.1024(2) | −1.97 | 0.1034(6) | −2.46 | 0.1011(2) | −1.17 |
| $A_{\mathrm{FB}}^{0,c}$ | [2] | 0.0707(35) | 0.0731(2) | −0.69 | 0.0739(4) | −0.90 | 0.0721(2) | −0.41 |
| $A_b$ | [2] | 0.923(20) | 0.93456(3) | −0.58 | 0.9347(1) | −0.58 | 0.93442(3) | −0.57 |
| $A_c$ | [2] | 0.670(27) | 0.6675(1) | 0.09 | 0.6681(4) | 0.07 | 0.6667(2) | 0.12 |