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Anomalous Magnetic Moments in and Beyond the Standard Model

SUSY, 23.08.2021

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_μ and consequences for future measurements
- Correlations with the electron AMM and implications for the muon EDM
- Further Flavour anomalies and future prospects

SM Theory Prediction: EW and QED

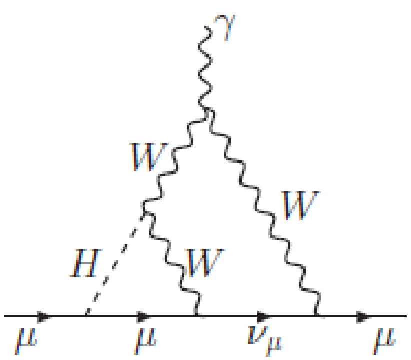
- QED 5-loop contribution T. Aoyama, T. Kinoshita, M. Nio, PRD, 2018

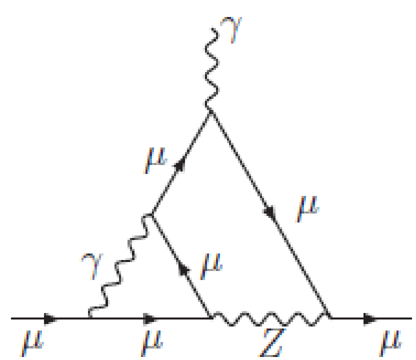
$$a_\mu(QED) \approx 116584718.951(0.080) \times 10^{-11}$$

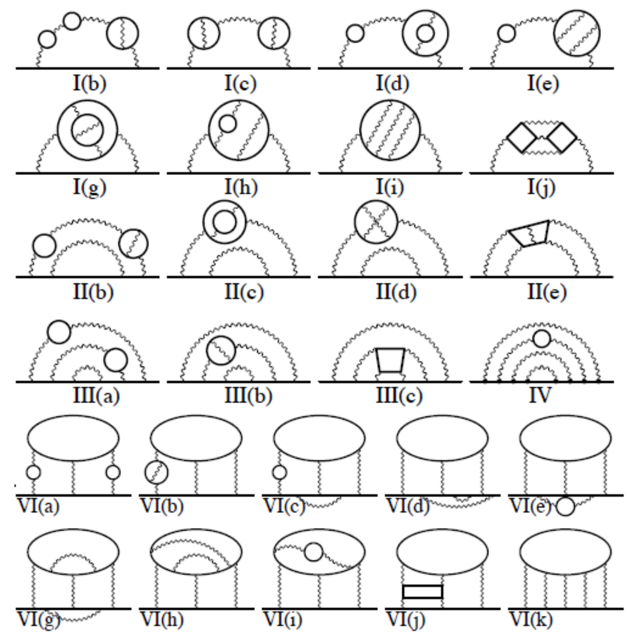
- EW 2-loop effect

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

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

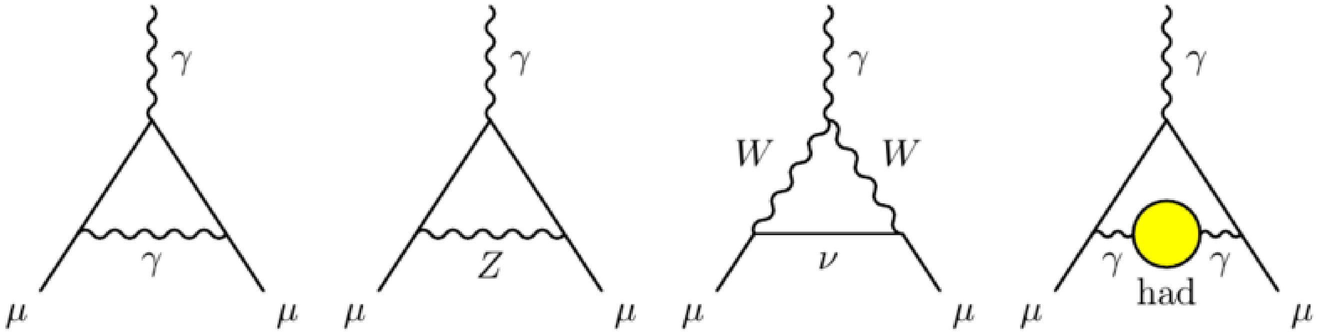






QED and EW well under control

Muon Anomalous Magnetic Moment



- Theory prediction challenging (hadronic effects)

$$\Delta a_\mu = (251 \pm 49) \times 10^{-11}$$ T. Aoyama et al., arXiv:2006.04822

- Need NP of the order of the SM EW contribution
- Chiral enhancement necessary for heavy NP
- Soon more experimental results from Fermilab
- Vanishes for $m_\mu \to 0$ ⇨ **measure of LFUV**

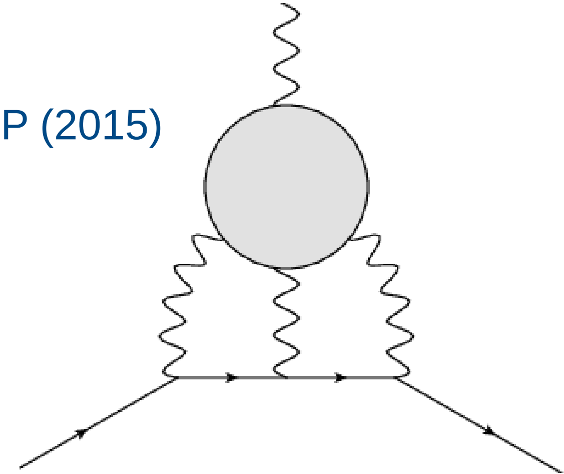
4.2σ deviation from the SM prediction

SM Theory: Hadronic Effects

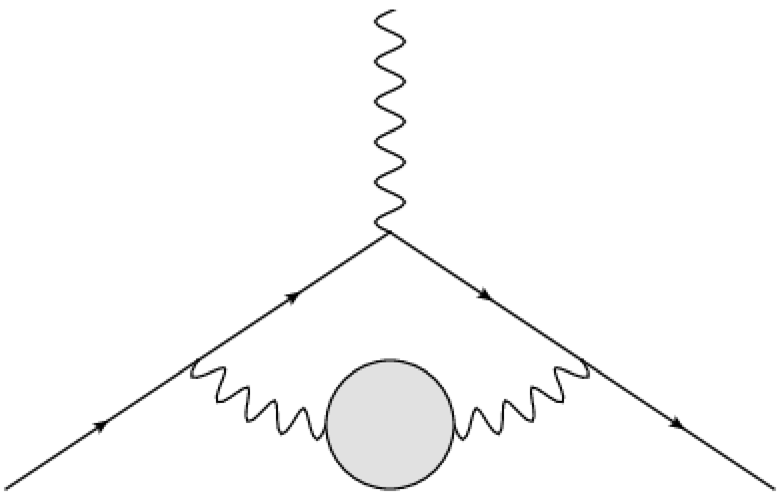
- Hadronic light-by-light scattering

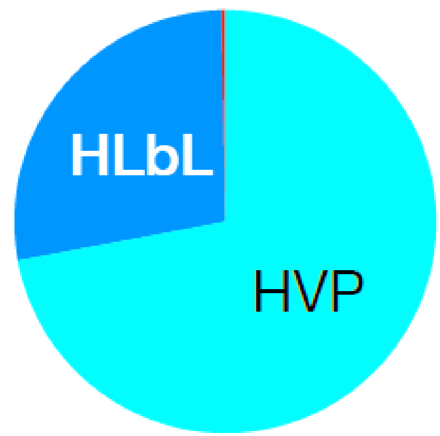
  G. Colangelo, M. Hoferichter, M. Procura, P. Stoffer, JHEP (2015)

  - 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

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

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

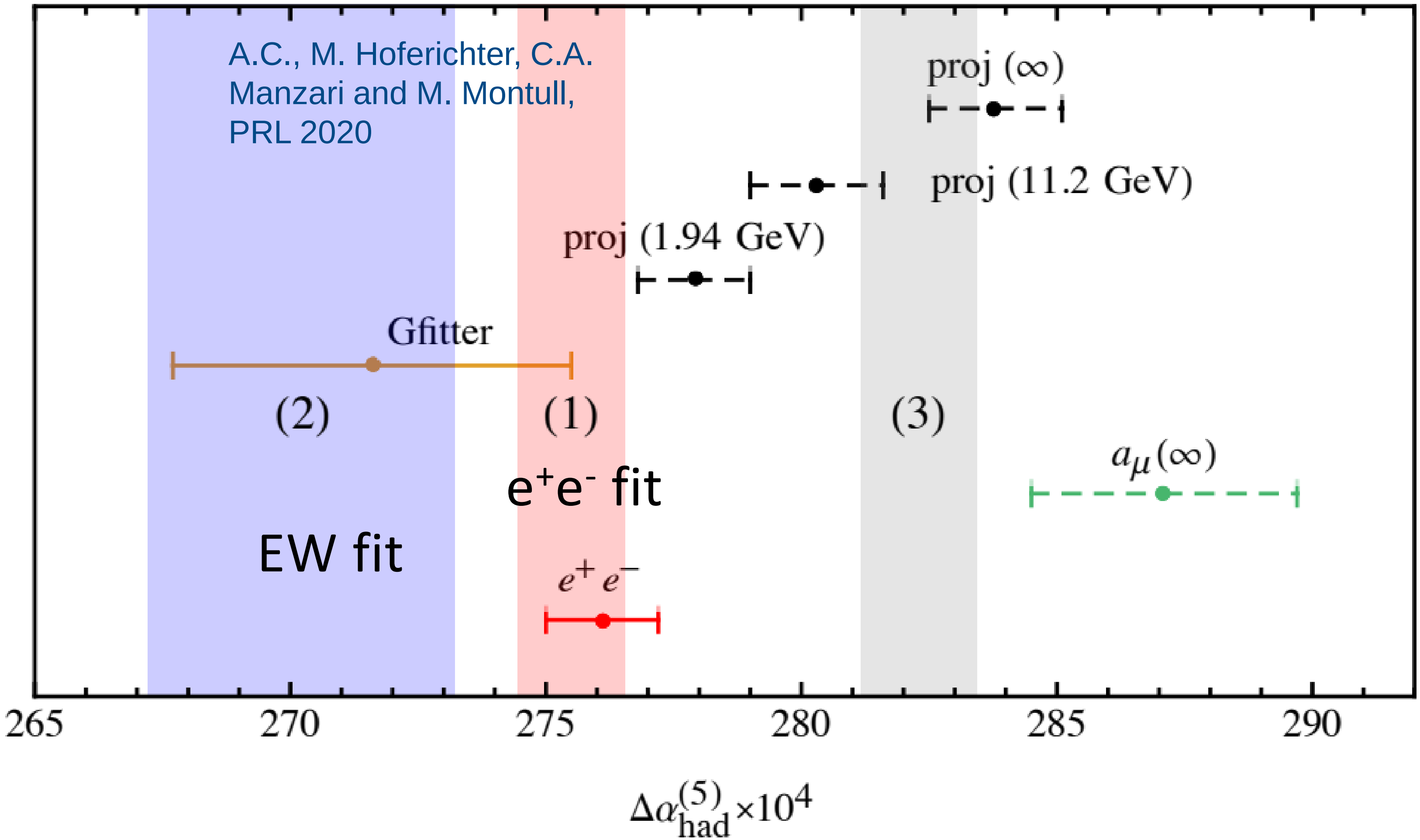
$$\Delta\alpha_{\mathrm{had}}^{(5)}\Big|^{\leq 1.94} = 277.9(1.1)\times 10^{-4},$$

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

(energy dependence not know)

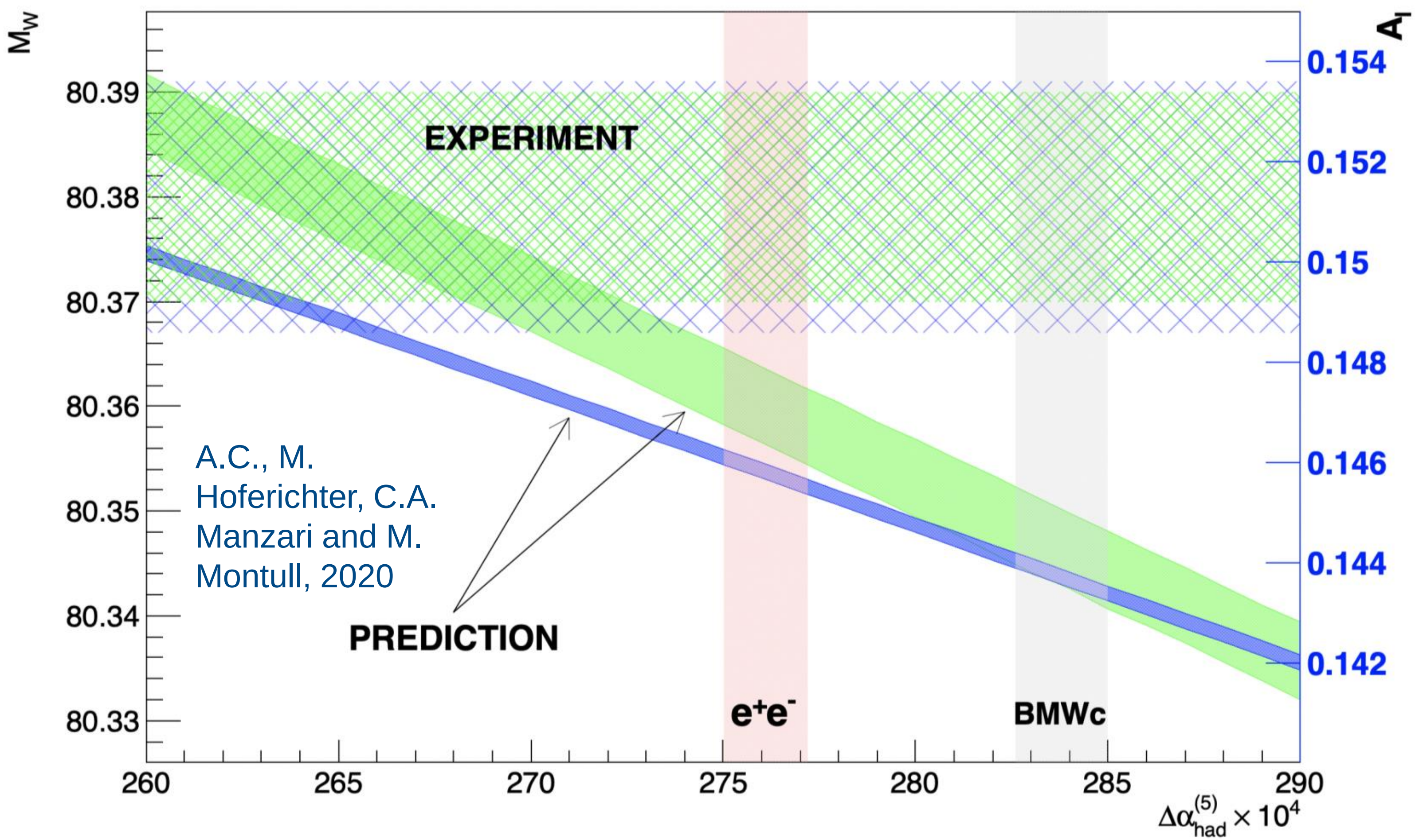
BMWc result in tension with e^+e^-; would solve g-2

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

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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

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

- Electric Dipole moment

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

- 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 f, g A loop functions

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

A priori arbitrary phase ➔ muon EDM

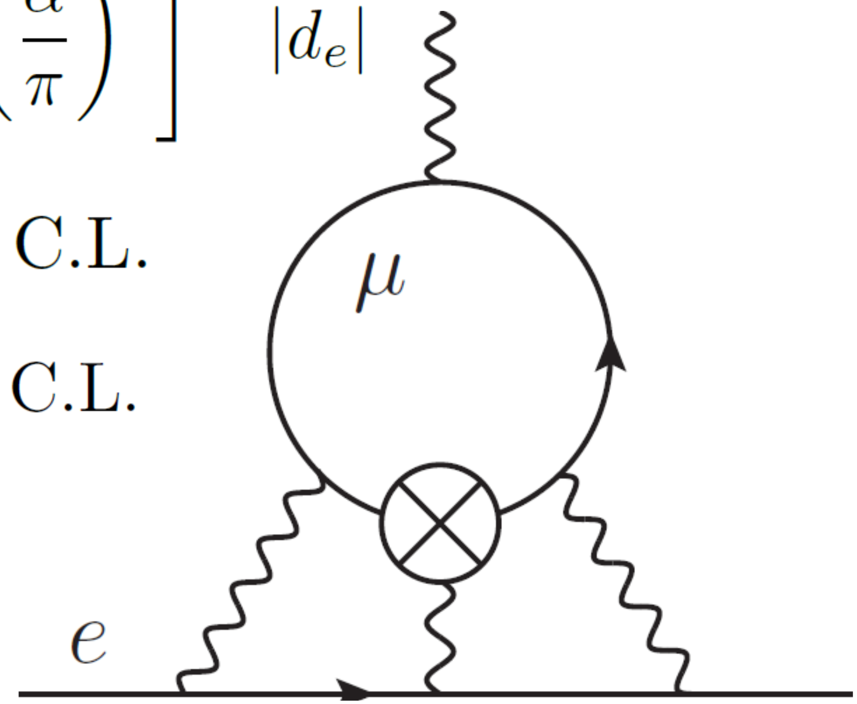
Indirect Limit on the Muon EDM

- MFV: $|d_\mu^{\mathrm{MFV}}| < 3.7 \times 10^{-24} e\,\mathrm{cm}$
- Contribution only starts at the 3-loop level

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

$$\leq 7.5 \times 10^{-19} e\,\mathrm{cm} \qquad 90\%\ \mathrm{C.L.}$$

$$|d_e| < 8.7 \times 10^{-29} e\,\mathrm{cm} \qquad 90\%\ \mathrm{C.L.}$$

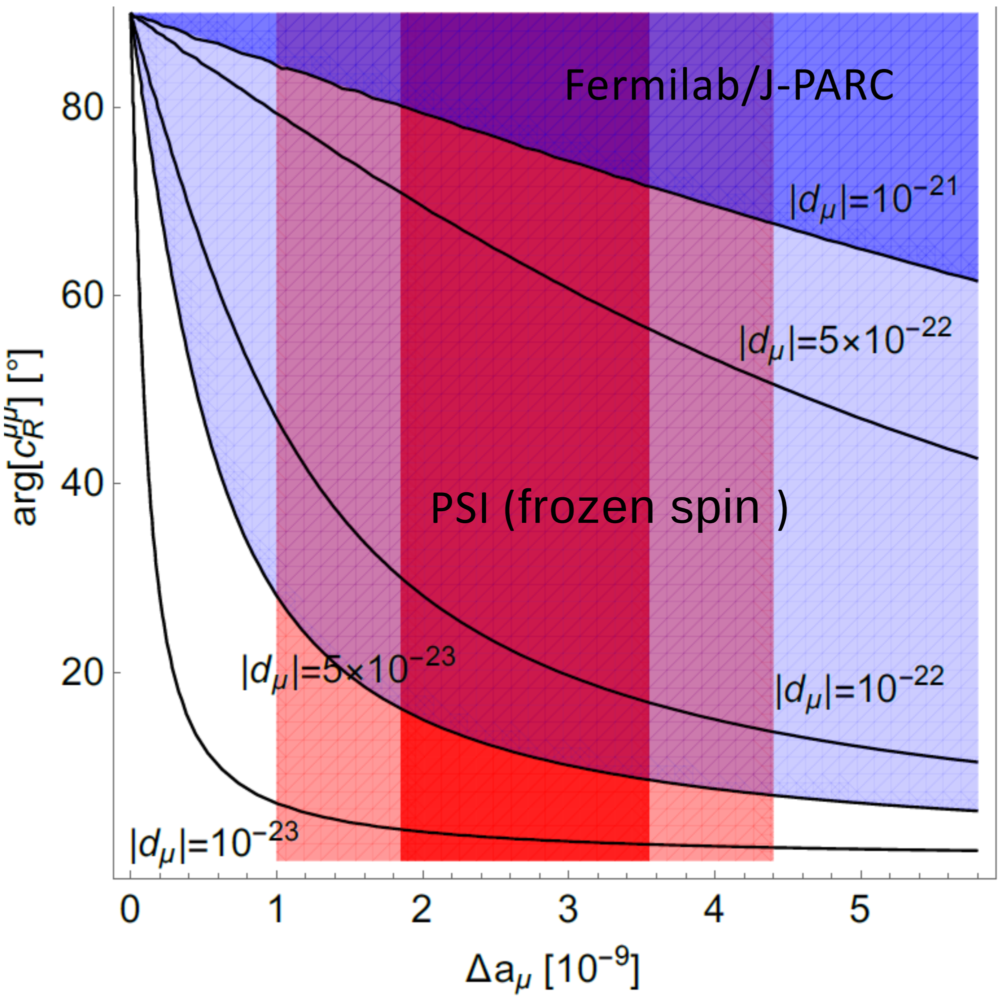


- Direct limit

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

Improvement of direct limit important

Future experimental sensitivity



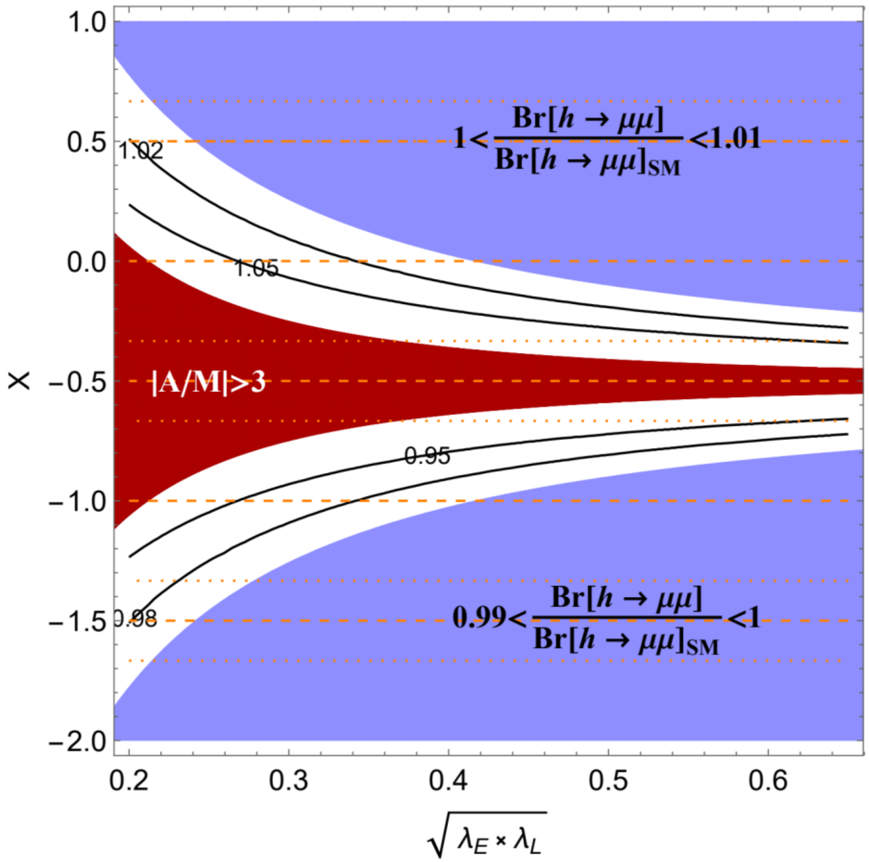
Dedicated experiment needed!

Heavy new scalars and fermions

- Chirally enhanced effects requires three fields

	R	Ψ, Φ	Φ_L, Ψ_L	Φ_E, Ψ_E	ϕ	ℓ	e
$SU(2)_L$	121	1	2	1	2	2	1
	212	2	1	2			
	323	3	2	3			
	232	2	3	2			
Y		X	$-\frac{1}{2} - X$	$-1 - X$	$\frac{1}{2}$	$-\frac{1}{2}$	-1

A.C., M. Hoferichter, 2104.03202

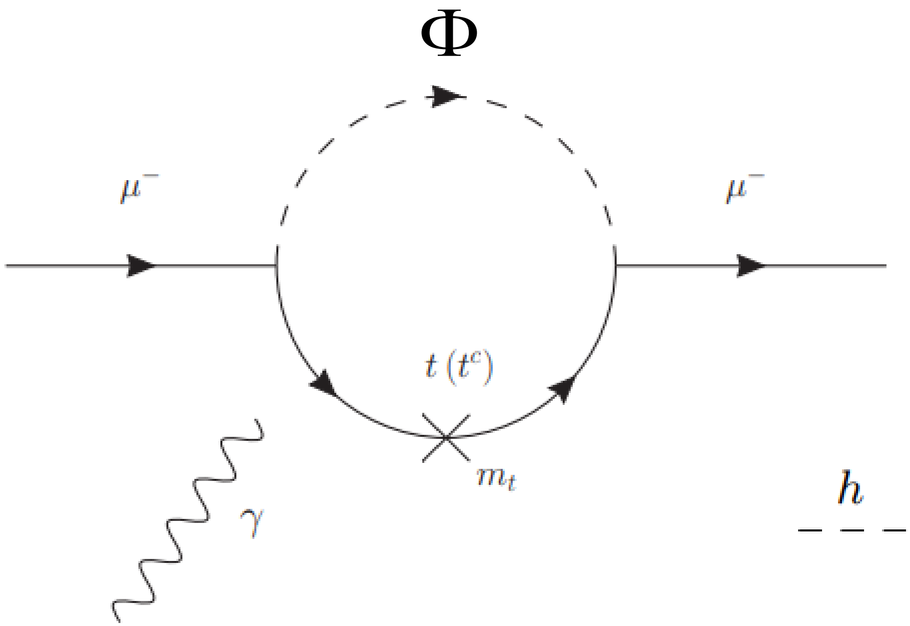


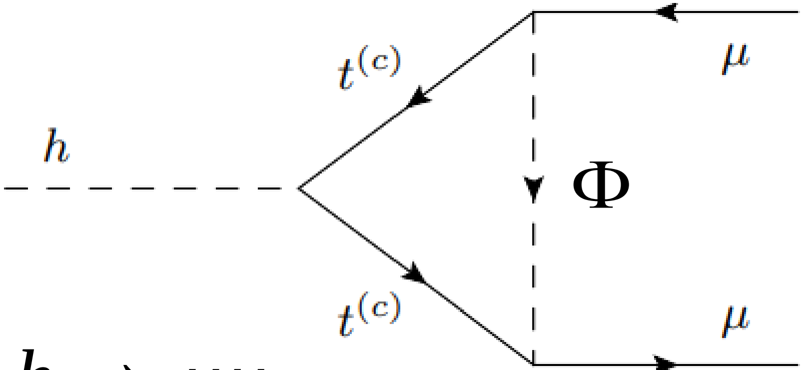
- SMEFT Matching
- Correlations with
  - Z→μμ
  - h →μμ

Z,h→μμ at future colliders

Leptoquarks in a_μ

- Chirally enhanced effects via top-loops



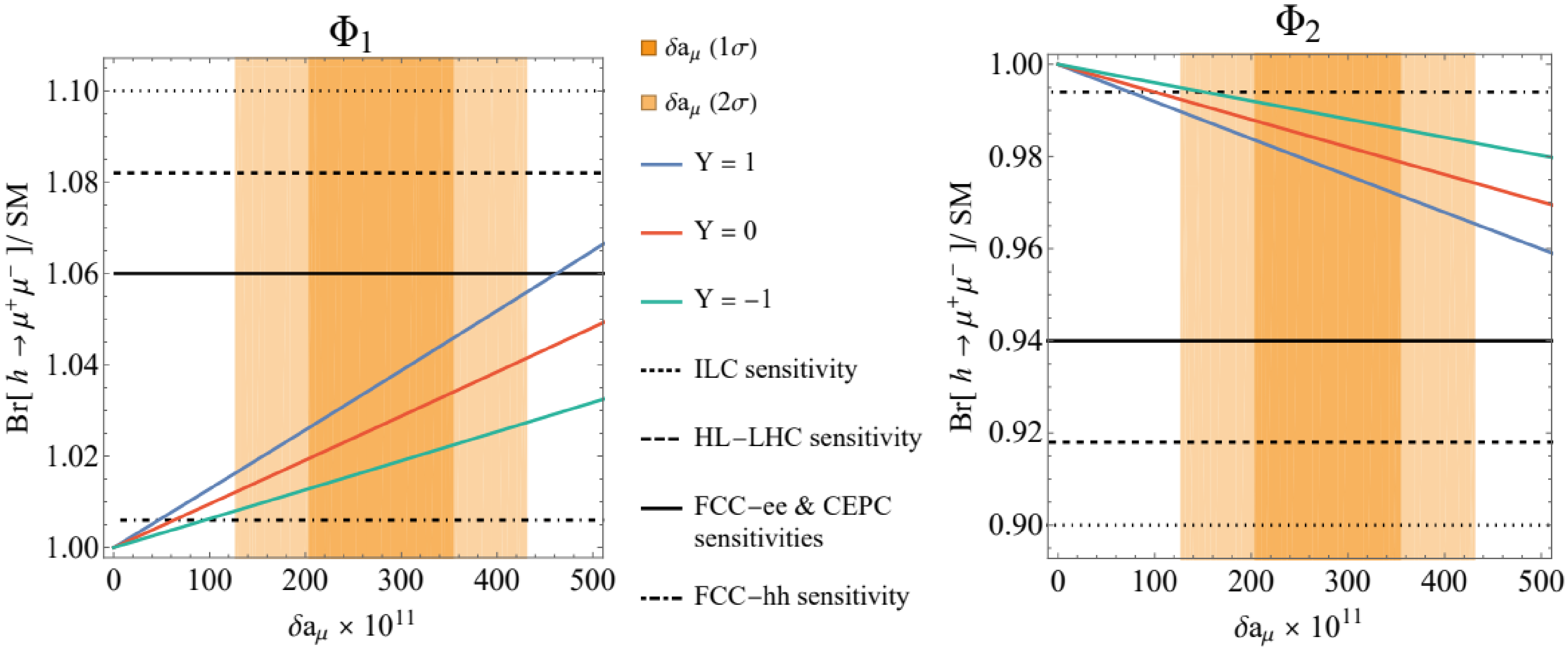


- m_t / m_μ enhanced effect $h \to \mu\mu$
- m_t^2 / m_Z^2 enhanced effect in $Z \to \mu\mu$

Correlations with h→μμ and Z→μμ

a_μ vs $h \to \mu\mu$

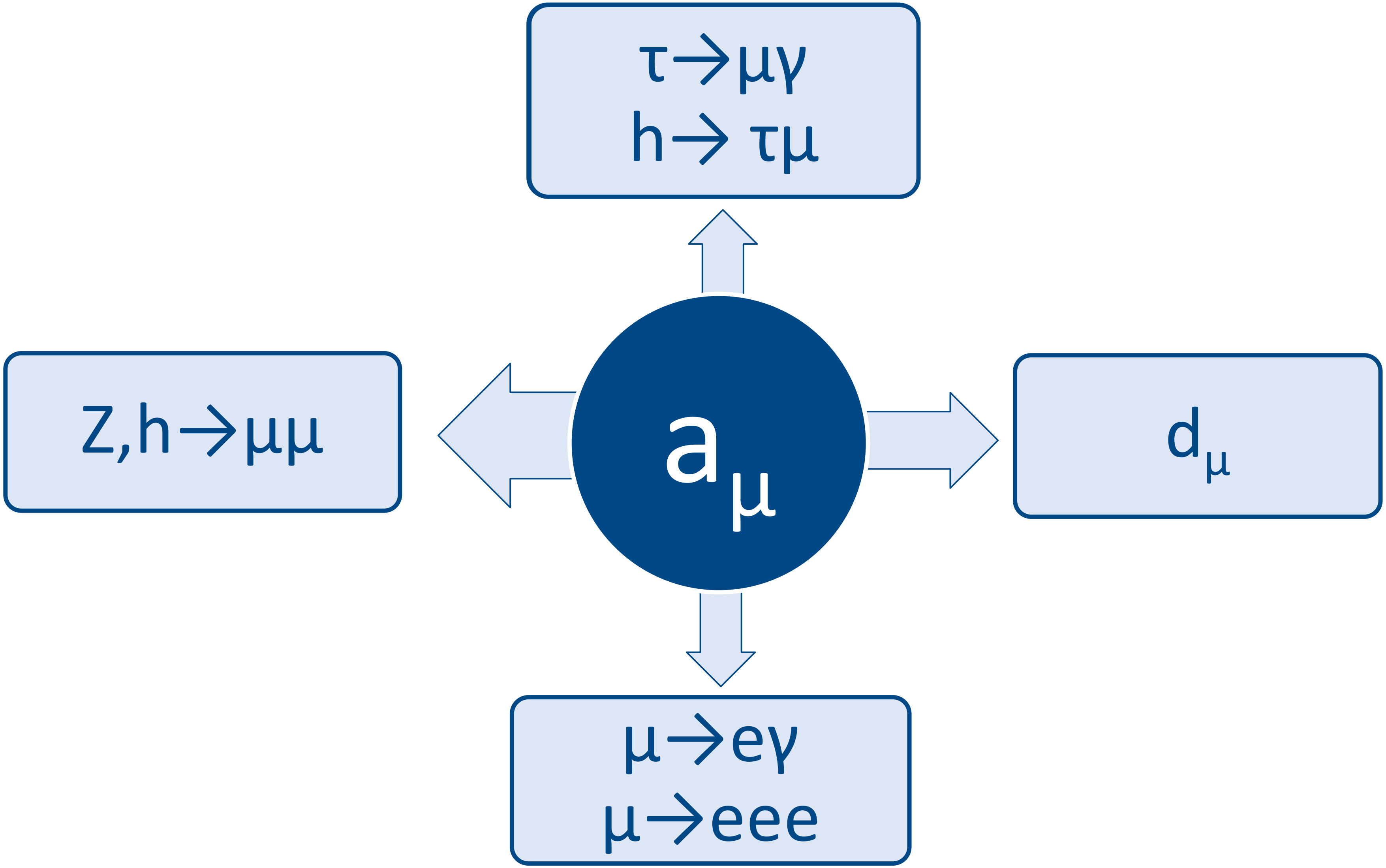
- Chirally enhanced effects via top-loops
- Same coupling structure → direct correlation



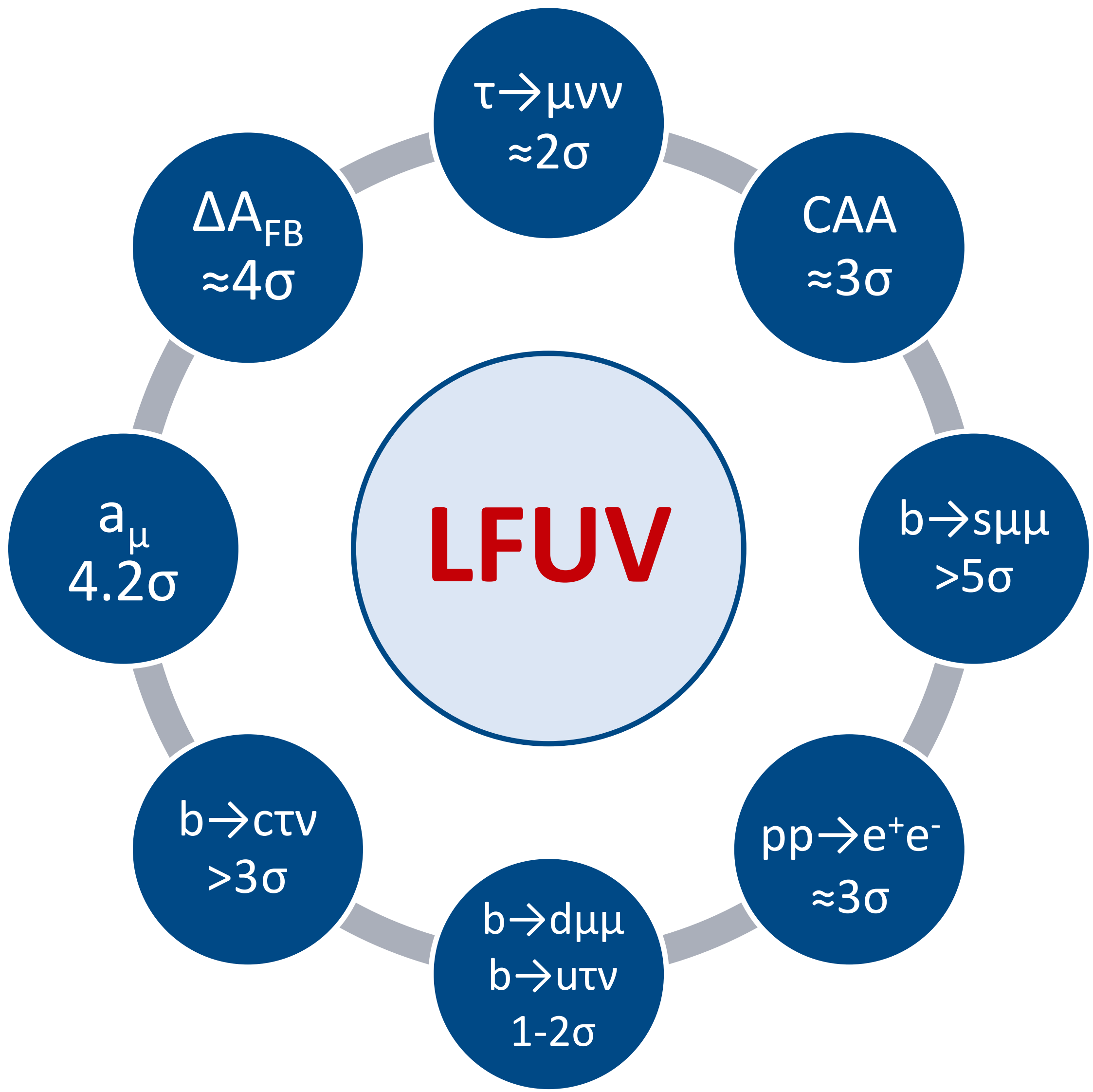
A.C., D. Mueller, F. Saturnino, 2008.02643

h→μμ at future colliders

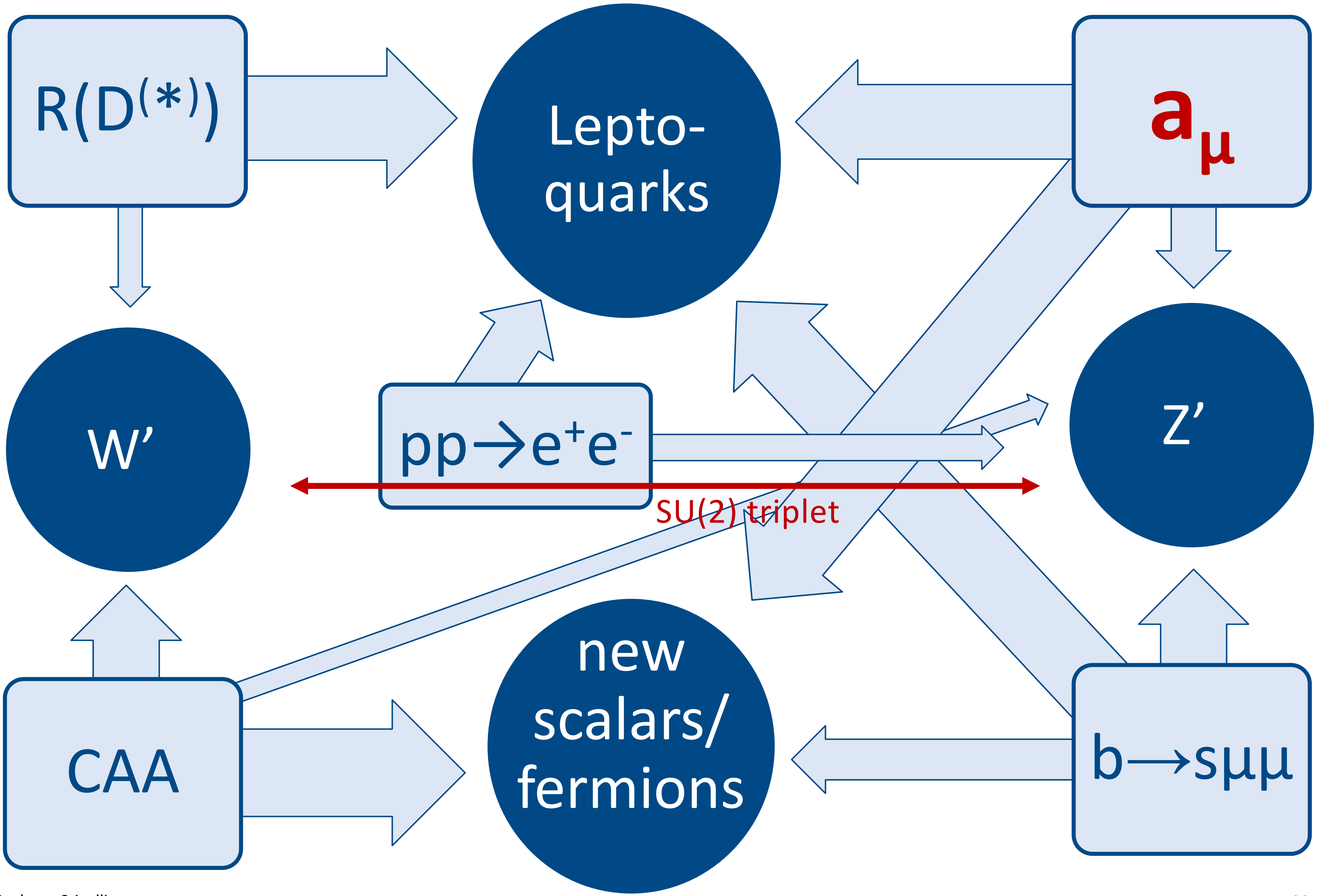
Future Implications of a_μ



Flavour Anomalies

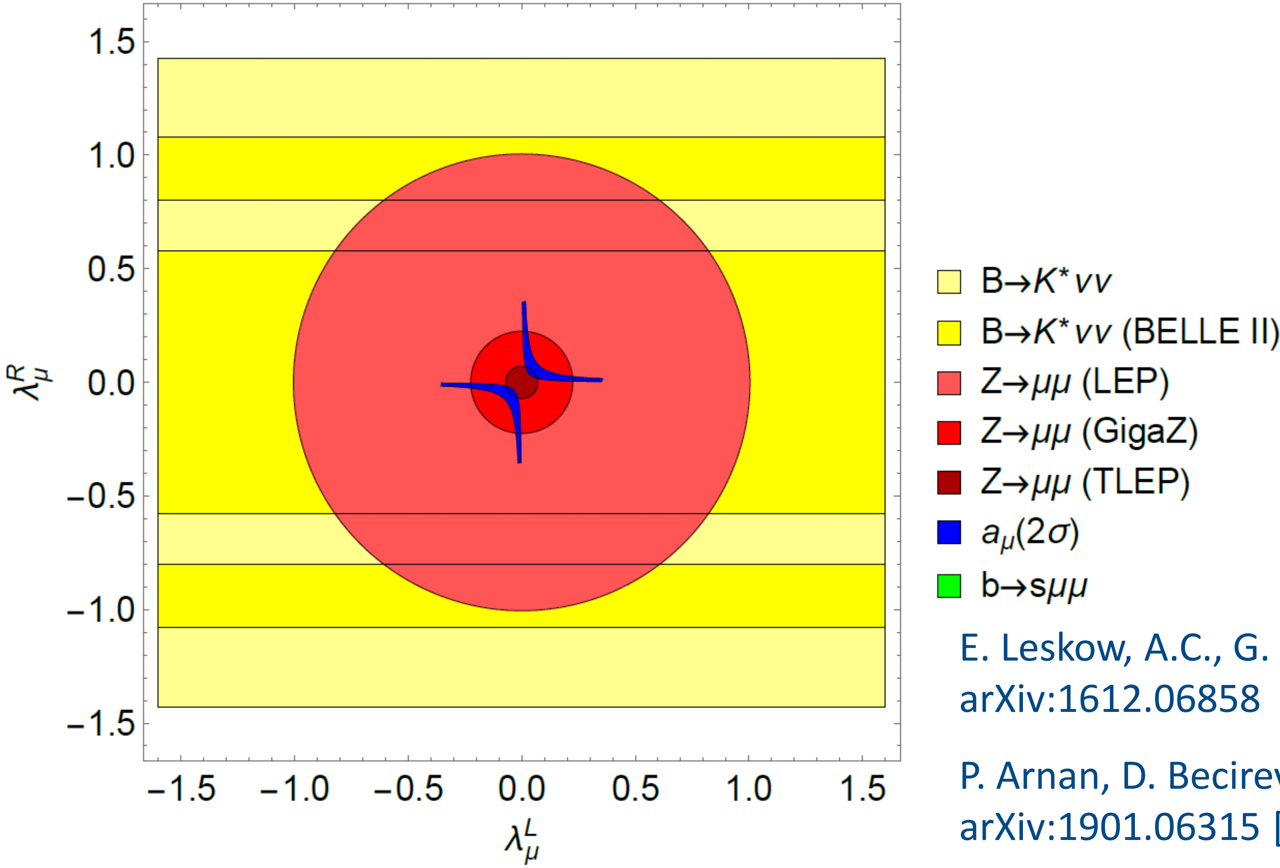


Conclusions



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

Backup

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
Γ_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_τ^{pol}	[2]	0.1465(33)	0.1461(3)	0.13	0.1475(8)	−0.28	0.1443(3)	0.68
A_ℓ	[2]	0.1513(21)	0.1461(3)	2.47	0.1475(8)	1.71	0.1443(3)	3.31
Γ_Z [GeV]	[2]	2.4952(23)	2.4947(6)	0.22	2.4951(6)	0.05	2.4942(6)	0.43
σ_h^0 [nb]	[2]	41.541(37)	41.485(6)	1.50	41.485(6)	1.51	41.485(6)	1.50
R_ℓ^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