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Naturalness of lepton non-universality and muon $g-2$

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ABSTRACT

We show that the observed anomalies in the lepton sector can be explained in extensions of the Standard Model that are natural and, therefore, resolve the Higgs sector hierarchy problem. The scale of new physics is around the TeV and Technicolor-like theories are ideal candidate models.

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Naturalness has been a driving principle for the past decades when modelling and searching for new physics. The observation of the Higgs boson, with properties similar to the ones predicted by the Standard Model (SM), not followed by the discovery of new particles has cast doubts on this guidance principle. In truth, the natural models disfavoured by experiments are vanilla extensions that predict a sizeable number of states below the TeV scale, such as the constrained minimal supersymmetric SM and composite Higgs models with several light top partners.

In this paper we show that the experimental observation of lepton non-universal processes together with the muon $g-2$ anomaly brings back naturalness as a prime motor for generating new models of fundamental interactions. Marrying Technicolor-like models [1,2] with SM fermion partial compositeness [3], we show that it is possible to accommodate the observed anomalies (for earlier attempts see [4,5]). The composite scale is around 2 TeV, which is the natural techni-fermion condensation scale. As for the Higgs nature, the fact is that strong dynamics is not easy to solve and the jury is still out on what this state could be. For example, it could emerge as a near dilaton [6–12] in walking Technicolor dynamics [13,14]. In this case, the associated effective action is implemented, following Coleman [15], by saturating the underlying trace anomaly of the theory. In recent years there has been interest in this type of effective framework [9–12,16–20] partially fuelled by lattice investigations. These are about $SU(3)$ gauge theories with $N_f = 8$ fundamental Dirac fermions [21–24], as well as $N_f = 3$

symmetric 2-index Dirac fermions (sextets) [25–27]. The latter are known as Minimal Walking Technicolor [9,10,28,29] models. For all these models, the lattice collaborations reported evidence for the existence of a light singlet scalar particle. A light Higgs state could also emerge due to top quark corrections, as pointed out in [30], and/or emerging from non QCD-like dynamics [9,30]. Another possibility is the composite Goldstone Higgs paradigm [31,32] that is, however, disfavoured by the muon $g-2$ anomaly, as we will show. For a general review of composite dynamics, we refer the reader to [33]. A discussion of naturalness and the muon $g-2$ anomaly in supersymmetric models can be found in [34,35], while for other perturbative explanations see [36] and references therein.

The Fermilab collaboration recently presented their first preliminary measurement of the muon anomalous magnetic moment [37], confirming a discrepancy from the SM value (by 3.3σ). Combining this result with the BNL E821 one [38] leads to the experimental average of

$$a_\mu(\text{Exp}) = 116\,592\,061(41) \times 10^{-11} \quad (0.35 \text{ ppm}), \quad (1)$$

with an overall deviation from the SM central value [39] of

$$\Delta a_\mu = a_\mu(\text{Exp}) - a_\mu(\text{SM}) = (251 \pm 59) \times 10^{-11}, \quad (2)$$

corresponding to a significance of 4.2σ [37].

Few weeks earlier the LHCb [40] collaboration presented their updated measurement of the ratio R_K , which is an important test of lepton universality in the SM:

$$R_K = \frac{\text{BR}(B^+ \rightarrow K^+ \mu^+ \mu^-)}{\text{BR}(B^+ \rightarrow K^+ e^+ e^-)} = 0.846_{-0.041}^{+0.044}. \quad (3)$$

This measure also deviates from the SM predictions at a 3.1σ level.

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Table 1

Quantum numbers of the new fermions \mathcal{F} and scalars \mathcal{S} in the model. \mathcal{G}_{TC} can be considered either gauged, as in composite scenarios, or global in a renormalisable model of flavour.

	\mathcal{G}_{TC}	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$
\mathcal{F}_L	F	1	2	Y
\mathcal{F}_N^c	$\bar{\mathbf{F}}$	1	1	$-Y - 1/2$
\mathcal{F}_E^c	$\bar{\mathbf{F}}$	1	1	$-Y + 1/2$
S_E^j	F	1	1	$Y - 1/2$
S_D^j	F	3	1	$Y + 1/6$

By comparing elementary and composite extensions of the SM, we show that Technicolor-like models [1,2] yield a natural interpretation of these results with imminent consequences for collider physics. We start by noticing that both R_K and Δa_μ are observables strongly related to the Yukawa sector of the SM, meaning that to explain the anomalies the new physics is related to the fermion mass generation mechanism. In fact, to account for the observed Δa_μ anomaly a new Higgs sector is crucial.

To better elucidate our point we employ a model that, depending on the underlying dynamics, can be interpreted as either elementary, or partially elementary, or fully composite. Without further ado, we add to the SM Lagrangian the following interactions:

$$-\mathcal{L}_{\text{NP}} = y_L^{ij} L^i \mathcal{F}_L (S_E^j)^* + y_E^{ij} (E^i)^c \mathcal{F}_N^c S_E^j + y_Q^{ij} Q^i \mathcal{F}_L (S_D^j)^* + y_U^{ij} (U^i)^c \mathcal{F}_E^c S_D^j + y_D^{ij} (D^i)^c \mathcal{F}_N^c S_D^j + \sqrt{2}\kappa (\mathcal{F}_L \mathcal{F}_N^c + \mathcal{F}_E \mathcal{F}_L^c) \phi_H + \text{h.c.} \quad (4)$$

where \mathcal{F} and \mathcal{S} are (Weyl) fermions and scalars, respectively, with multiplicity N_{TC} . We will interpret this multiplicity either as a global number or as the dimension of the fundamental representation of a new confining gauge group \mathcal{G}_{TC} . Their specific quantum numbers are listed in Table 1. In the Lagrangian (4), L , E and Q are the usual chiral SM fields, while ϕ_H is a state with the Higgs doublet quantum numbers.

We list below the various underlying interpretations of the model:

- i) New elementary fermions and scalars with renormalisable interactions that radiatively contribute to the SM fermion masses. An interesting limit occurs when the flavour structure of the SM fermion masses is radiatively generated by loops of \mathcal{F} and \mathcal{S} , hence the flavour structure is encoded in the new Yukawa couplings rather than in the Higgs couplings. Here, \mathcal{F} are vector-like (thus they have both chiralities) and have a tree-level mass $M_{\mathcal{F}}$.
- ii) The Higgs of the SM is replaced by a Technicolor composite state of (non) Goldstone nature, while the new scalars are still elementary, as put forward in fundamental partial compositeness [41] (see also [42–44]). This implies that κ models the coupling between the effective Higgs field and its constituents. The fermions \mathcal{F} can be chiral or vector-like, depending on the details of the model.
- iii) As in ii) but with the new scalars interpreted as effective operators made of new extended Technicolor fermions [33]. This limit covers also models of partial compositeness presented in [45,46].

For case i), due to the perturbative nature of the loops, the masses of the heavy fermions (top, and possibly also bottom, tau and charm) still originate from direct Higgs Yukawa interactions, while lighter masses and flavour mixing may be radiatively generated.

For cases ii) and iii), \mathcal{G}_{TC} confines at low energies and generates the Higgs as a composite (Goldstone) meson. Here, in addition to their eventual bare masses, the new fermions \mathcal{F} and scalars \mathcal{S} will acquire a dynamical mass upon condensation, equal to a fraction of the condensation scale Λ_{TC} .

In Table 2 we summarise the expressions that we use to analyse the data relevant for the flavour and muon $g - 2$ anomalies. In particular, $c_{b_L \mu_L}$ dominates the leptonic B decays relevant for the R_K and R_{K^*} measurements, while $C_{B\bar{B}}$ encodes the strongest constraint from the B_s mixing [47]. The latter constraint provides an upper bound on the quark Yukawa combination $(y_Q y_Q^\dagger)_{bs}$, which we fix to suitable values in our numerical analysis. Finally we consider the correction to the Z coupling to muons. The Yukawa combination $(y_L y_L^\dagger)_{\mu\mu}$ also generates corrections to muon coupling to the Higgs, which is however far from the current measurements. Observables involving other flavours, like $K - \bar{K}$ mixing or lepton flavour violating processes, also impose very strong bounds, however on different combinations of the Yukawas (for instance, $(y_Q y_Q^\dagger)_{sd}$ for Kaon mixing and $(y_L y_L^\dagger)_{\mu e}$ for $\mu \rightarrow e\gamma$ and the likes). As their relation to muon anomalies is model-dependent, we do not consider them here. In the second column of the Table we show the perturbative estimate of the muon $g - 2$ stemming from loops of the heavy fermions and scalars. The associated Naive Dimensional Analysis (NDA) estimate from composite dynamics is displayed in the third column. For Δa_μ , the relevant charges read $q_{\mathcal{F}} = Y + 1/2$ and $q_{S_E} = Y - 1/2$ with Y the hypercharge of the fermion doublet \mathcal{F}_L . For the elementary case the hypercharge is chosen to yield integer charges for the non QCD-coloured states, in particular for the plots we assume $Y = 1/2$. For the composite case the hypercharge depends on the details of the model, in particular on N_{TC} . For example, for $N_{\text{TC}} = 2$ we have $\mathcal{G}_{\text{TC}} = SU(2)$ with $Y = 0$, leading to the model studied in [48,49]. In this model with two Dirac techni-fermions, one can simultaneously accommodate composite Goldstone Higgs and Technicolor models [50] and lattice have confirmed the pattern of chiral symmetry breaking $SU(4)$ to $Sp(4)$ [51–53]. For the traditional Technicolor case of $N_{\text{TC}} = 3$ it is possible to assume the value $Y = 1/2$. Additionally, in the composite theory, $g_{\text{TC}} \sim \frac{4\pi}{\sqrt{N_{\text{TC}}}}$ takes care of varying number of Technicolors and the Yukawa couplings in Eq. (4) appear in the combinations $\frac{yY}{g_{\text{TC}}}$, which is assumed to be a perturbative coupling in the effective field theory description of the composite models. In the NDA estimates, it is not possible to know, a priori, the sign of the coefficients. Hence, we take the sign from the loop effects with equal masses: for Δa_μ the contribution is positive, as required by the measured muon $g - 2$, for $Y = 0$ or positive.

We start with the new physics explanation coming from a composite nature of the SM Higgs sector together with (fundamental) partial compositeness for the fermions. The results are summarised in Fig. 1 for a model featuring $N_{\text{TC}} = 2$ and $Y = 0$, where the “ R_K ” bound only takes into account the new measurement in Eq. (3) (more details in the Appendix). From the NDA estimate, Δa_μ is mostly sensitive to the scale of new physics Λ_{TC} with a mild dependence on the left-handed muon Yukawa, as it is visible from the near vertical green bands. They are based on the deviation from the SM world averages reported in [39]. Here we learn that the muon $g - 2$ anomaly requires a rather low composite scale of the order of 2 TeV, independently on other parameters of the model. At the same time, in order to address the R_K anomaly, a large left-handed muon Yukawa coupling is required with values compatible with composite dynamics represented by the region below the horizontal grey dashed line. Except Δa_μ , all contributions in Table 2 are suppressed by a factor g_{TC}^{-2} showing that a careful analysis of effective operators [56] is needed when estimating new physics contribution from composite dynamics. In

Table 2

Coefficients of the low-energy operators impacting leptonic B decays ($c_{b_L\mu_L}$), B_s mixing ($C_{B\bar{B}}$), correction to the Z coupling to muons and the muon $g-2$, estimated via perturbative loops of the heavy fermions and scalars (second column) [47,54,55] or via their strongly-interacting NDA (third column). For Δa_μ , the relevant charges read $q_{\mathcal{F}} = Y + 1/2$ and $q_{S_E} = Y - 1/2$. In the composite models, $m_\mu \sim N_{\text{TC}} \frac{(y_L y_E^\dagger)_{\mu\mu} \kappa v_{\text{SM}}}{(4\pi)^2}$. The loop functions, where $x = M_{S_D}^2/M_{\mathcal{F}}^2$ and $y = M_{S_E}^2/M_{\mathcal{F}}^2$, are given in the appendix.

Coefficient	Perturbative one-loop result	Non-perturbative NDA
$c_{b_L\mu_L}$	$N_{\text{TC}} \frac{(y_L y_L^\dagger)_{\mu\mu} (y_Q y_Q^\dagger)_{bs}}{(4\pi)^2 M_{\mathcal{F}}^2} \frac{1}{4} F(x, y)$	$\frac{(y_L y_L^\dagger)_{\mu\mu} (y_Q y_Q^\dagger)_{bs}}{g_{\text{TC}}^2 \Lambda_{\text{TC}}^2}$
$C_{B\bar{B}}$	$N_{\text{TC}} \frac{(y_Q y_Q^\dagger)_{bs}}{(4\pi)^2 M_{\mathcal{F}}^2} \frac{1}{8} F(x, x)$	$\frac{(y_Q y_Q^\dagger)_{bs}}{g_{\text{TC}}^2 \Lambda_{\text{TC}}^2}$
$\delta g_{Z\mu_L}$	$N_{\text{TC}} g_2 \frac{M_{\mathcal{F}}^2 (y_L y_L^\dagger)_{\mu\mu}}{(4\pi)^2 2(1 - 2s_W^2) M_{\mathcal{F}}^2} F_9(Y, y)$	$g_2 \frac{M_{\mathcal{F}}^2 (y_L y_L^\dagger)_{\mu\mu}}{g_{\text{TC}}^2 \Lambda_{\text{TC}}^2}$
Δa_μ	$N_{\text{TC}} \frac{m_\mu (y_L y_E^\dagger)_{\mu\mu} \kappa v_{\text{SM}}}{(4\pi)^2 M_{\mathcal{F}}^2} [2q_{S_E} F_{LR}(y) + 2q_{\mathcal{F}} G_{LR}(y)] +$ $N_{\text{TC}} \frac{m_\mu^2 (y_L y_L^\dagger)_{\mu\mu}}{(4\pi)^2 M_{\mathcal{F}}^2} [2q_{S_E} F_7(y) + 2q_{\mathcal{F}} \bar{F}_7(y)]$	$\frac{m_\mu^2}{\Lambda_{\text{TC}}^2} \left(1 + \frac{(y_L y_L^\dagger)_{\mu\mu}}{g_{\text{TC}}^2} \right)$

particular, the correction to the Z coupling to left-handed muons is negligible [47].

The low composite scale disfavours composite Goldstone Higgs (CGH) dynamics, which needs a little hierarchy between the composite and electroweak scale, thus leaving a Technicolor-like explanation for the anomalies. This conclusion is also supported by independent estimates of Δa_μ for CGH dynamics [57,58] which read:

$$\Delta a_\mu (\text{CGH}) \approx \frac{g_*^2}{(4\pi)^2} \frac{m_\mu^2}{m_*^2} = \frac{v_{\text{SM}}^2}{f_{\text{CGH}}^2} \frac{m_\mu^2}{\Lambda_{\text{TC}}^2}, \quad (5)$$

with $m_* = g_* f_{\text{CGH}}$ and $\Lambda_{\text{TC}} \approx 4\pi v_{\text{SM}} \approx 2$ TeV. Here, f_{CGH} is the Goldstone Higgs decay constant, and it is expected to assume a value substantially above the TeV scale to ensure a Goldstone nature of the Higgs and to reduce the tension with electroweak precision bounds.

The situation can improve for the CGH scenario if the latest lattice results from the BMW collaboration [59], not included in the world average, are considered as the true contribution to the hadronic vacuum polarisation of the photon [60–62]. These are represented by the yellow bands in Fig. 1. However, in the BMW scenario it is harder to account for R_K for fixed N_{TC} , and it emerges a tension with electroweak precision [63]. This is so since it would require a too large muon left-handed Yukawa coupling. These results hold for both cases ii) and iii) on the model list. A way out is to increase N_{TC} .

It is useful to compare the composite scenario with its perturbative and elementary alter ego. The radiative explanation depends on three heavy particles masses, two scalars and one fermion. Furthermore, the ordinary Higgs Yukawa coupling to the new heavy fermions κ yields the dominant contribution to the muon $g-2$ and therefore we further maximize it by requiring it to saturate the muon mass [64] according to

$$m_\mu = N_{\text{TC}} \frac{(y_L y_E^\dagger)_{\mu\mu} \kappa v_{\text{SM}}}{(4\pi)^2} \ln \frac{\Lambda^2}{M_{\mathcal{F}}^2}, \quad (6)$$

with Λ a high energy cutoff interpreted as the scale at which the effective muon Yukawa vanishes. Without the Higgs corrections the model was investigated in [65] and because of this it cannot account for the observed $g-2$ of muon.

We are now ready to illustrate the radiative results in Fig. 2. After imposing the relation in Eq. (6), Δa_μ depends only on the masses of \mathcal{F} and S_E , and on Y . In the left panel, we show the allowed regions from the $g-2$ for $Y = 1/2$. The green bands highlight an upper bound on the fermion mass at 1.5 TeV, while low

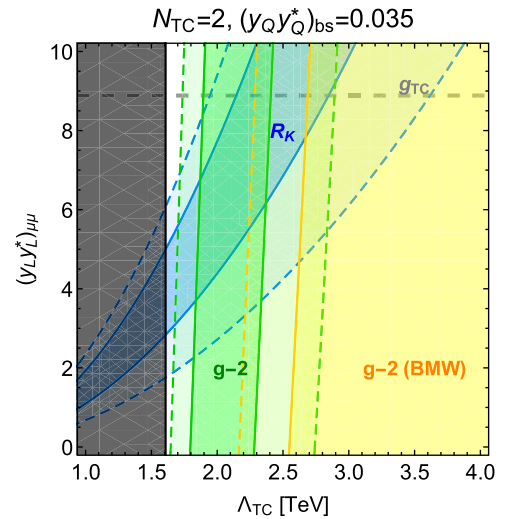


Fig. 1. Parameter space of the model following the NDA estimates. The green bands fit the muon $g-2$ anomaly following the world average for the SM prediction [39]. The blue regions fit R_K , while the shaded grey area is excluded by the B_s oscillations. The solid (dashed) lines indicate 1σ (2σ) regions. The yellow area corresponds to the muon $g-2$ anomaly if the recent BMW lattice calculation [59] is used for the hadronic photon polarisation. The horizontal grey line marks the value of the muon y_L for which $(y_L y_L^\dagger)_{\mu\mu} = g_{\text{TC}}$.

masses can also be reached at the price of heavier scalars. For comparison, we also show the region allowed by the BMW results. To reproduce R_K we must consider also the mass of the colour-triplet scalar S_D : being charged under QCD, its mass is strongly constrained by the LHC searches, with precise bounds depending on the decays. We thus fix its mass to a benchmark value of 1.5 TeV. In the right panel we show the dependence on the muon left-handed Yukawa and on the multiplicity N_{TC} for benchmark values of the masses that reproduce the muon $g-2$ anomaly. The general trend is that R_K requires either large Yukawas or large field multiplicity, the latter constrained by the B_s mixing. The main drawback of this scenario is that the Yukawas tend to develop a Landau pole at low scales, thus limiting the validity range of the model [47].

To conclude, the anomalies associated to the muon physics can be successfully addressed within Technicolor-like models. The scale of new physics is around 2 TeV implying that new massive states, such as the techni-rho, are within reach of the LHC direct searches [66,67]. The composite Goldstone Higgs scenario is disfavoured by the low composite scale and perturbative elementary extensions

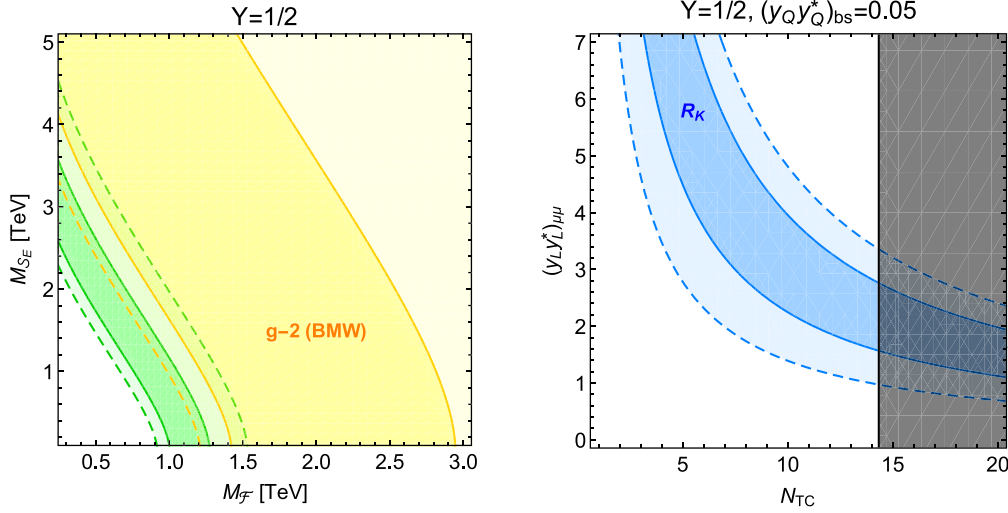


Fig. 2. Parameter space of the model following the loop estimates from Table 2. In the left panel, we show the regions preferred by the muon $g-2$ anomaly as a function of the two relevant masses, $M_{\mathcal{F}}$ and M_{S_E} . In the right plot, we explore R_K for a representative choice of masses that reproduces the $g-2$ anomaly: $M_{\mathcal{F}} = 1$ TeV, $M_{S_E} = 0.9$ TeV and $M_{S_D} = 1.5$ TeV. In both cases, $Y = 1/2$. We maximise the Higgs contribution to the Δa_{μ} considering that the SM muon Yukawa coupling is radiatively generated following Eq (6) (with $\Lambda = 5M_{\mathcal{F}}$).

suffer from large muon left-handed Yukawa couplings and unnaturally large multiplicity of new fields.

If the anomalies are confirmed by future experimental analyses, our results show that naturalness plays a fundamental role when constructing theories of nature, with impact in other realms from dark matter model building and searches to addressing the dark energy problem in cosmology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A

The loop functions used in Table 2 have been extracted from [54,55,65] and adapted to our model. They are given by:

$$F(x, y) = \frac{1}{(1-x)(1-y)} + \frac{x^2 \ln x}{(1-x)^2(x-y)} + \frac{y^2 \ln y}{(1-y)^2(y-x)}, \quad (\text{A.1})$$

$$F(x, x) = \frac{1-x^2+x \ln x}{(1-x)^3}, \quad (\text{A.2})$$

$$F_7(y) = \frac{2+3y-6y^2+y^3+6y \ln y}{12(1-y)^4}, \quad (\text{A.3})$$

$$\begin{aligned} \tilde{F}_7(y) &= \frac{F_7(y^{-1})}{y} \\ &= \frac{1-6y+3y^2+2y^3+6y^2 \ln y}{12(1-y)^4}, \quad (\text{A.4}) \end{aligned}$$

$$F_{LR}(y) = \frac{1-y^2+2y \ln y}{2(1-y)^3}, \quad (\text{A.5})$$

$$G_{LR}(y) = \frac{1+4y+3y^2-2y^2 \ln y}{2(1-y)^3}; \quad (\text{A.6})$$

$$\begin{aligned} F_9(Y, y) &= s_W^2(2Y-1) \frac{11-18y+9y^2-2y^3+6 \ln y}{36(1-y)^4} \\ &- (1-s_W^2(2Y+1)) \frac{7-36y+45y^2-16y^3+6(2y-3)y^2 \ln y}{36(1-y)^4}; \quad (\text{A.7}) \end{aligned}$$

where $x = M_{S_D}^2/M_{\mathcal{F}}^2$ and $y = M_{S_E}^2/M_{\mathcal{F}}^2$.

The bound on R_K used in this work derives from the most recent measurement in Eq. (3). We use the approximate formula [47]

$$R_K \approx 1 + 2 \frac{\text{Re } c_{b_L \mu_L}}{c_{b_L \mu_L}^{\text{SM}}}, \quad (\text{A.8})$$

where $c_{b_L \mu_L}^{\text{SM}} = 8.64$.

To impose the B_s mixing bound we use the fit at 2σ from Ref. [65]

$$C_{B\bar{B}} \in [-2.1, 0.6] \cdot 10^{-5} \text{ TeV}^{-2}. \quad (\text{A.9})$$

Finally, for the Z coupling to muons, we use the LEP [68] measurement $g_{Z\mu_L} = -0.2689 \pm 0.0011$, leading to the 2σ bound

$$\left| \frac{\delta g_{Z\mu_L}}{g_{Z\mu_L}^{\text{SM}}} \right| \leq 0.8\%. \quad (\text{A.10})$$

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