Search for light dark vector boson: NA64 experiment

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In this mini review we outline the main experimental and theoretical results related with the search for light vector boson proposed as a solution of the muon $g-2$ anomaly. In particular, we consider a model with infinite number of light vector bosons which can escape most of current experimental bounds. We describe also the NA64 experiment at CERN devoted to the search for light vector boson both in visible and invisible decay modes.

1 Introduction

The search for new physics beyond the SM can be divided into two categories. The first one is the search for new heavy particles and interactions at high energies, the so-called "energy frontier" research. Typical examples are LEP, Tevatron and LHC. The second type of research is the search for relatively light with masses $m \leq O(1)\ GeV$ new hypothetical particles. In this case an experiment needs to cross the "intensity frontier". The most famous example of light hypothetical particle is the axion [1], invented for the solution of strong CP-problem. Also there are models predicting the existence of light scalar, spin 1/2 and vector particles. In particular, models with light vector bosons [2] (vector portal) become rather popular now. Light vector boson can be mediator between our world and light dark matter particles [2]. Also light vector boson can explain [3] - [8] muon $(g-2)$ anomaly [9]. Recent claim [10] of the discovery of 17 MeV vector particle observed as a peak in e^+e^- invariant mass distribution in nuclear transitions makes the question of possible existence of light vector boson extremely interesting and important.

In this mini review we outline the main experimental and theoretical results related with the search for light vector boson. In particular. we consider a model with infinite number of light vector bosons which can escape most of current experimental bounds. We also describe the NA64 experiment at CERN devoted to the search for light vector boson both in visible and invisible decay modes.

2 Muon $g-2$ anomaly and the light Z' boson.

Recent precise measurement of the anomalous magnetic moment of the positive muon $a_\mu = (g-2)/2$ from Brookhaven AGS experiment 821 [9] gives result which is about 3.6σ higher [11] than the Standard Model prediction

$$a_\mu^{exp} - a_\mu^{SM} = 288(80) \times 10^{-11} \tag{1}$$

This result may signal the existence of new physics beyond the Standard Model. New light (with a mass $m_{Z'} \leq O(1)\ GeV$) vector boson (dark photon) which couples very weakly with muon with $\alpha_{Z'} \sim O(10^{-8})$ can explain $(g-2)$ anomaly [3]-[8]. Vectorlike interaction of Z' boson with muon

$$L_{Z'} = g^{`} \bar{\mu}\gamma^\mu \mu Z'_\mu \tag{2}$$

leads to additional contribution to muon anomalous magnetic moment [12]

$$\delta a = \frac{\alpha^{`}}{2\pi} F(\frac{m_{Z'}}{m_\mu}), \tag{3}$$

where

$$F(x) = \int_0^1 dz \frac{[2z(1-z)^2]}{[(1-z)^2 + x^2 z]} \tag{4}$$

and $\alpha^{`} = \frac{(g^{`})^2}{4\pi}$. Equation (4) allows to determine the coupling constant $\alpha^{`}$ which explains the value (1) of muon anomaly. For $m_{Z'} \ll m_\mu$ one can find that

$$\alpha^{`} = (1.8 \pm 0.5) \times 10^{-8}. \tag{5}$$

For another limiting case $m_{Z'} \gg m_\mu$ the $\alpha^{`}$ is

$$\alpha^{`} = (2.7 \pm 0.7) \times 10^{-8} \times \frac{m_{Z'}^2}{m_\mu^2}. \tag{6}$$

But the postulation of the interaction (2) of the Z_μ boson with muon is not the end of the story. The main question: what about the interaction of the Z' boson with other quarks and leptons? The most general renormalizable Z' interaction with the SM fermions ψ_k ($\psi_k = e, \nu_e, u, d, ...$) has the form

$$L_{Z'} = g^{`} Z'_\mu J^\mu_{Z'}, \tag{7}$$

$$J^\mu_{Z'} = \sum_k [q_{Lk}\bar{\psi}_{Lk}\gamma^\mu\psi_{Lk} + q_{Rk}\bar{\psi}_{Rk}\gamma^\mu\psi_{Rk}], \tag{8}$$

where $\psi_{Lk,Rk} = \frac{1}{2}(1 \mp \gamma_5)\psi$ and q_{Lk}, q_{Rk} are the Z' charges of the ψ_{Lk}, ψ_{Rk} fermions. The Z' can interact with other beyond SM particles, for instance, with dark matter fermions χ

$$L_{Z',\chi} = g_D Z'_\mu \bar{\chi}\gamma^\mu\chi. \tag{9}$$

There are several models of the current $J^\mu_{Z'}$. In a model [13, 14] Z' interacts with photon A_μ due to kinetic mixing term[1]

$$L_{mix} = \frac{\epsilon}{2} F^{\mu\nu} Z'_{\mu\nu}. \tag{10}$$

As a result of the mixing (10) the field Z' interacts with the SM electromagnetic field $J^\mu_{EM} = \frac{2}{3}\bar{u}\gamma^\mu u - \frac{1}{3}\bar{d}\gamma^\mu d - \bar{e}\gamma^\mu e + ...$ with coupling constant $g^{`} = \epsilon e$ ($\alpha = \frac{e^2}{4\pi} = \frac{1}{137}$) .

[1]Here $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ and $Z'_{\mu\nu} = \partial_\mu Z'_\nu - \partial_\nu Z'_\mu$.

Other interesting scenario is the model [15] where Z' (the dark leptonic gauge boson) interacts with the SM leptonic current, namely

$$L_{Z'} = g'[\bar{e}\gamma^\nu e + \bar{\nu}_{eL}\gamma^\nu \nu_{eL} + \bar{\mu}\gamma^\nu \mu + \bar{\nu}_{\mu L}\gamma^\nu \nu_{\mu L} + \bar{\tau}\gamma^\nu \tau + \bar{\nu}_{\tau L}\gamma^\nu \nu_{\tau L}]Z'_\nu$$

In Refs. [3] - [5] for an explanation of $g-2$ muon anomaly a model where Z' interacts with $L_\mu - L_\tau$ current with an interaction

$$L_{Z'} = g'[\bar{\mu}\gamma^\nu \mu + \bar{\nu}_{\mu L}\gamma^\nu \nu_{\mu L} - \bar{\tau}\gamma^\nu \tau - \bar{\nu}_{\tau L}\gamma^\nu \nu_{\tau L}]Z'_\nu \tag{11}$$

has been proposed. The interaction (12) is free from γ_5-anomalies, it commutes with the SM gauge group and moreover it escapes (see next section) from the most restrictive current experimental bounds because the interaction (12) does not contain quarks and first generation leptons ν_e, e.

3 Model with infinite number of light Z' bosons

Here we consider model with infinite number of light vector bosons which can escape current experimental bounds. The models with infinite number of local fields have been considered in Refs.[16, 17, 18]. Note that notion of an unparticle, introduced by Georgi [19, 20] can be interpreted as a particular case of such models [16, 17, 21, 22, 23]. So we consider a model with infinite number of vector fields $Z'_{\mu n}$ with masses $m_{Z'_n}$. We introduce the "effective" vector field $Z'_\mu = \sum_n c_n Z'_{\mu n}$[2] and postulate the interaction of the electromagnetic field A_μ with the the effective field Z'_μ in the form of kinetic mixing term (10). As a result of mixing the effective field Z'_μ will interact with the SM electromagnetic current with coupling constant $g^{'} = \epsilon e$. The one-loop contribution to δa is $\delta a = \sum_n |c_n^2| \frac{\alpha^{'}}{2\pi} F(\frac{m_{Z'_n}}{m_\mu})$. The effectic field Z'_μ represents the infinite number of vector resonances that helps to escape bounds related with the search for narrow resonance in e^+e^- invariant mass distribution [18]. We can speculate that the origin of the infinite number of local vector fields as a result of compactification of some additional dimension. Namely, we can imagine the model with vector field $Z'_\mu(x, x_5)$ living in five-dimensional world and interacting with the four-dimensional SM fields due to kinetic mixing term

$$L_{mix} = \frac{\epsilon}{2} F^{\mu\nu}(x) Z'_{\mu\nu}(x, x_5 = 0)$$

After compactification of the x_5 coordinate we obtain the model (10) with the interaction of the effective field Z' with the SM electromagnetic current.

4 Accelerator experimental bounds

4.1 Fixed target electron experiments

Fixed target experiments, APEX [24] and MAMI(Mainz Microtron) [25] searched for Z' in electron-nucleus scatterings using the Z' bremsstrahlung production $e^- Z \to e^- Z Z'$ and subsequent Z' decay into electron-positron pair $Z' \to e^+e^-$. The absence of the resonant peak

[2]Here c_n are some numbers

in the invariant e^+e^- mass spectrum allows to obtain upper limits on the Z' boson coupling constants g_{Ve}, g_{Ae} of the Z' with electron. The A1 collaboration excluded the masses $50\ MeV < M_{Z'} < 300\ MeV$ [25] for $g-2$ muon anomaly explanation in the model with equal muon and electon couplings of the Z' boson with a sensitivity to the mixing parameter up to $\epsilon^2 = 8 \times 10^{-7}$. APEX collaboration used $\sim 2\ GeV$ electron beam at Jefferson Laboratory and excluded masses $175\ MeV < M_{Z'} < 250\ MeV$ for $g-2$ muon anomaly explanation in the model with equal muon and electon couplings of the Z' boson.

4.2 e^+e^- experiments

BaBar experiment searched for both visible and invisible Z' decays in $\Upsilon(1S)$ decays [26, 27, 28]. A search for invisible $\Upsilon(1S)$ has been performed by reconstructing $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$. The bound $Br(\Upsilon(1S) \to invisible) = (-1.6 \pm 1.4 \pm 1.6) \cdot 10^{-4}$ was found. Here the first uncertainty is statistical and the second systematic. In addition invisible decays can be searched for in radiative $\Upsilon(1S) \to \gamma +$ invisible decays. In particular, the decay $\Upsilon(1S) \to \gamma +$ invisible could proceed through production of a light scalar A followed the by its decay into invisible modes $\Upsilon(1S) \to \gamma + A$, $A \to$ invisible. The bound on $Br(\Upsilon(1S) \to \gamma + \text{invisible})$ was obtained at the level $(0.5 - 24) \cdot 10^{-5}$ assuming a phase-space distribution for photon energy. Visible decays of light Z' bosons were searched for in the reaction $e^+e^- \to \gamma Z'$, $Z' \to l^+l^-(l = e, \mu)$ and Z' can be detected as resonances in the l^+l^- spectrum. For the model with the Z' boson interaction with the SM electomagnetic current values of the mixing strength $10^{-3} - 10^{-2}$ are excluded for $0.212\ GeV < m_{Z'} < 10\ GeV$.

Recently BaBar collaboration used the reaction $e^+e^- \to Z'\mu^+\mu^-$, $Z' \to \mu^+\mu^-$ to search for Z' boson. The use of this process allows to restrict directly the muon coupling $g_{V\mu}$ of Z' boson. The obtained results exclude the Z' model with the $L_\mu - L_\tau$ interaction as possible muon $(g-2)$ anomaly explanation for $m_{Z'} > 212 MeV$ [29].

The KLOE detector experiment in Fraskati, at the DAΦNE Φ-factory searched for Z' in decays $\Phi \to \eta Z' \to \eta e^+e^-$ and $\Phi \to \gamma Z' \to \gamma\mu^+\mu^-$ [30]. Also the reaction $e^+e^- \to Z'\gamma \to e^+e^-\gamma$ has been used for the search for Z'. The obtained bounds are weaker than the NA48/2 [31] and MAMI [25] bounds.

4.3 Fixed target proton experiments

The most strongest bound comes from the NA-48/2 experiment [31]. The NA-48/2 experiment used simultaneous K^+ and K^- seconday beams produced by $400\ GeV$ primary CERN SPS protons for the search for light Z' boson in π^0 decays [31]. The decays $K^\pm \to \pi^\pm\pi^0$ and $K^\pm \to \pi^0\mu^\pm\nu$ have been used to obtain tagged π^0 mesons. The decays $\pi^0 \to \gamma Z^{`}$, $Z' \to e^+e^-$ have been used for the search for Z' boson. Z' boson manifests itself as a narrow peak in the distribution of the e^+e^- invariant mass. spectrum. For the model when the Z' boson interacts with the SM electomagnetic current as $L_{int,Z'} = \epsilon e Z'_\mu J^\mu_{SM}$ the obtained bounds exclude the $(g-2)$ muon anomaly explanation for Z' boson masses $9 MeV < m_{Z'} < 70\ MeV$ [31].

It should be noted that the decay width $\pi^0 \to \gamma Z'$ is proportional to $(g_{Vu}q_u - g_{Vd}q_d)^2 = (2g_{Vu} + g_{Vd})^2/9$ and for the models with nonuniversal Z'-boson couplings, for instance, for the model with $L_\mu - L_\tau$ interaction current the NA-48/2 bound [31] is not applicable.

4.4 Constraints from $K \to \pi + nothing$ decay

Light vector bosom Z' can be produced in the $K \to \pi Z'$ decay in full analogy with the SM decay $K \to \pi\gamma^*$ of K-meson into pion and virtual photon. For the model with the dominant Z' decay into invisible modes nontrivial bound on Z' boson mass and coupling constants arises. Namely, the BNL E949 experiment [32] combined with E787 results measured the $K^+ \to \pi^+\nu\bar{\nu}$ decay and gave upper bounds on the $Br(K^+ \to \pi^+ Z')$ decay as a function of the Z' mass in the assumption that invisible $Z' \to nothing$ decay dominates. The E949 + E787 bound leads to the bound on the Z' mass and coupling constants. For instance, in the model when Z' couple with the SM electromagnetic current and decays mainly into invisible modes(light dark matter) the muon $(g-2)$ anomaly explanation due to Z' is excluded for $M_{Z'} > 50\ MeV$ except the narrow region around $M_{Z'} = m_\pi$ [33] - [35]. Note that in the models with the Z' non electromagnetic current interaction, for instance in the model where the Z' interacts with the $L_\mu - L_\tau$ current, the bound from $K \to \pi + nothing$ decay decay does not work or it could be rather weak [34]. Recent result of NA64 collaboration [36] based on the use of the reaction $eZ \to eZZ'$, $Z' \to$ invisible gives the most powerful bound on dark matter Z' boson and excludes the region $M_{Z'} \leq 50\ GeV$ for muon $g-2$ anomaly explanation, see next section.

4.5 Bound from electron magnetic moment

The experimental and theoretical values for electron magnetic moment coincide at the 10^{-12} level of accuracy, namely [37]

$$\Delta a_e \equiv a_e^{exp} - a_e^{SM} = -(1.05 \pm 0.82) \times 10^{-12}\,. \qquad (12)$$

The Z' boson contributes to the Δa_e at one loop level, see formulae (3,4). From the bound (13) it is possible to restrict the couplng constants g_{Ve} and g_{Ae}. For the model with equal muon and electron couplings $g_{Ve} = g_{V\mu}$ and $g_{Ae} = g_{A\mu} = 0$ the $(g-2)$ muon anomaly explanation due to Z' existence is excluded for $M_{Z'} \geq 15\ MeV$ [38].

4.6 Constraints from $\nu - e$ scatterings

If the Z' boson couples with electron neutrino current and electron - the strongest bound arises from Borexino experiment [40]. Borexino experiment detects the low energy solar neutrino through elastic scattering of neutrino and electron [40]. The Z' exchange modifies the SM elastic electron neutrino electron cross section that allows to obtain strong constraint on the Z' coupling constants with electron neutrino and electron [41]. The obtained bound on $|g_{V\nu_e} \cdot g_{Ve}|^{1/2}$ is about 10^{-6} for $m_{Z'} \leq 1\ MeV$ and about 10^{-4} for $m_{Z'} \leq 100\ MeV$. Borexino data exclude the $(g-2)$ muon anomaly explanation in the model with Z' interaction with leptonic current [15]. Also the Borexino data exclude the model with the Z' interaction with the $B - L$ current.

4.7 Bound from $\nu_\mu N \to \nu_\mu N \mu^+\mu^-$

The neutrino trident $\nu_\mu N \to \nu_\mu N + \mu^+\mu^-$ events allow to restrict a model where Z' interacts with $L_\mu - L_\tau$ current using the data of the CHARM [42] and the CCFR [43] experiments. The CCFR and CHARM data on $\nu_\mu N \to \nu_\mu N + \mu^+\mu^-$ production exclude the $g-2$ muon anomaly explanation for Z'-boson mass $m_{Z'} \geq 400\ MeV$ [44].

4.8 Beam dump experiments

The results of beam dump experiments E137 [45], E141 [46] at SLAC and E774 [47] at FNAL have been used [2] to constrain the couplings of light gauge boson Z'. In recent paper [48] MiniBooNE-DM collaboration have obtained bound on $Y = \epsilon^2\alpha^{`}(\frac{m_\chi}{m_{Z'}})^4 \leq 10^{-8}$.

5 NA64 experiment at CERN. The first results

The NA64 experiment [49] at CERN is a fixed-target experiment searching for dark sector particles at the CERN Super Proton Synchrotron(SPS). If new light boson Z' exists it could be produced in the reaction of high-energy electrons scattering off nuclei. The NA64 experiment uses the bremsstrahlung reaction $eZ \to eZZ'$ for the search for Z' boson. Both visible $Z' \to e^+e^-$ and invisible $Z' \to$ invisible decays can be used for the search for Z' boson. Also the use of the secondary muon beams for the search for Z' boson in the reaction $\mu Z \to \mu Z Z'$ [50] is planned in the near future.

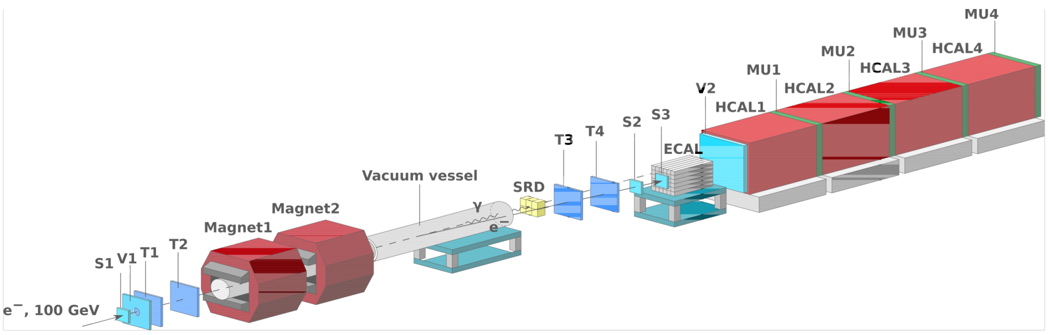

Figure 1: Schematic illustration of the setup to search for $Z' \to$ invisible decays for the bremsstrahlung Z' produced in the reaction of $eZ \to eZZ'$ of 100 GeV e^- incident on the active ECAL target [36].

The NA64 detector has two modifications for the search for both visible and invisible Z' decays. Here we outline the main features of NA64 detector used for the search for invisible Z' decays. The NA64 detector is schematically shown in Fig.1. The experiment employes the optimized 100 GeV electron secondary beam from CERN SPS. The detector utilises the beam defining scintillator (Sc) counters $S1 - S3$ and veto $V1$, and magnetic spectrometer consisting of two successive dipole magnets and a low-material-budget tracker. The tracker is a set of two upstream Micromegas chambers ($T1, T2$) and two downstream GEM stations ($T3, T4$) allowing the measurements of electron momenta with the precision $\delta p/p \approx 0.01$ [51]. The magnets also serves as an effective filter rejecting the low energy component of beam. To enhance the electron identification the synchrotron radiation (SR) emitted by electrons is used for their effective tagging. A 15 m long vacuum vessel between the magnets and the electromagnetic calorimeter (ECAL) is installed to minimize absorption of the SR photons detected immediately at the downstream end of the vessel with a SR detector (SRD), which is eihther an array of $Bi_4Ge_3O_{12}$(BGO) cristals of a $PbSc$ sandwich calorimeter of a very fine segmentation [52]. By using the SRD, the initial level of the hadron contamination in the beam $\pi/e \leq 10^{-2}$ is further suppressed by a factor $\approx 10^{-3}$. The detector is also equipped with an active target, which is an electromagnetic calorimeter for measurement of the electron energy deposition E_{ECAL} with the accuracy $\delta E_{ECAL}/E_{ECAL} \approx 0.1/\sqrt{E_{ECAL}}$. The ECAL is a matrix of 6×6 Shashlik-type modules assembled from Pb ans Sc plates with wave length shifting fiber read-out. Each module has ≈ 40 radiation length. Downstream of ECAL the detector is equipped with a high-efficiency veto counter $V2$ and a massive, hermetic hadronic calorimeter (HCAL) of a ≈ 30 nuclear lengths. The HCAL serves as an effective veto to detect muons of hadronic secondairies produced in the $e^- A$ interactions in the target. The HCAL energy resolutions is $\delta E_{HCAL}/E_{HCAL} \approx 0.6/\sqrt{E_{HCAL}}$. Four muon plane counters MU1 - MU4, located between the HCAL modules are used for the muon identification in the final state.

The method of the search for Z' is as follows [36]. As a result of the reaction $e^- Z \to eZZ'$ of the Z' electroproduction on nuclei with subsequent Z' decay $Z' \to \chi\chi$ into dark matter particles χ we expect events whose signature is a single electromagnetic (EM) shower in the target with energy E_e accompanied by a significant missing energy $E_{miss} = E_0 - E_e$ above those expected from backgrounds. Here we assume that dark matter particles traverse the detector without interaction or visible decays in order to give a missing energy signature. No other assumptions on the nature of the $Z' \to$ invisible decay are made. Other signature of the signal event is small energy deposited in HCAL.

During summer 2016 run NA64 experiment collected approximately 2.75×10^9 electrons on target [36]. Candidate events were requested to have the missing energy in the range $50 < E_{miss} < 100\ GeV$, which was selected based on the calculation of the energy spectrum of Z' emitted in the reaction $eZ \to eZZ'$ by e^- from the EM shower generated by electron beam in the target [53]. Zero events have been observed and as a consequence the 90% $C.L.$ upper limit for the average number of signal events $N_{Z'} = 2.3$ has been derived. The obtained results [36] exclude the invisible Z' as an explanation of the muon anomaly with masses $m_{Z'} \leq 100\ MeV$ in the model with the Z' inreraction with the SM electromagnetic current, see Fig.2. Only small mass region around $m_{Z'} = m_\pi$ is still allowed. The future NA64 runs with $\geq 5 \times 10^{10}$ electrons on target can test the remaining mass region around $m_{Z'} = m_\pi$.

5.1 Conclusions

Current experimental data restrict rather strongly the explanation of the $g-2$ muon anomaly due to existence of new light gauge boson but not completely eliminate it. The most popular model where Z' interacts with the SM electromagnetic current due to mixing $\frac{\epsilon}{2}F_{\mu\nu}Z^{\mu\nu}$ term is excluded except its modification in which the invisible decay Z' dominates. In this case the narrow mass region around $m_{Z'} \sim m_\pi$ is still allowed. The Borexino data on neutrino electron elastic scattering exclude the models with Z' interaction with both leptonic current and $B-L$ currents. The interaction of the $Z^{'}$ boson with $L_e - L_\mu$ current is excluded for $m_{Z'} \geq 214\ MeV$. The review of nonaccelerator bounds can be found in Ref.[54].

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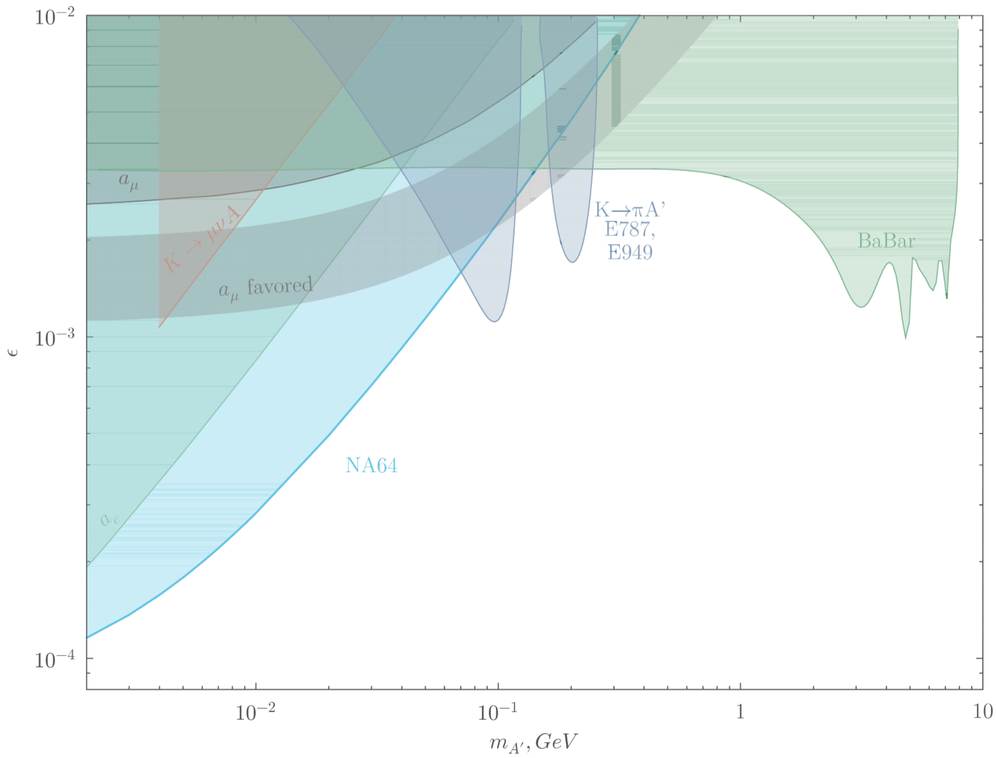

Figure 2: The NA64 90 % C.L. exclusion region in the ($m_{Z'}$, ϵ) plane. Constraints from BaBar and E787 + E949 experiments, as well the muon $(g-2)$ favoured area are also shown [36].

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