Gauged $L_\mu - L_\tau$ symmetry

Phenomenology

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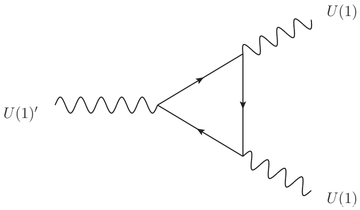
Outline

Anomalies

- The standard model (massless neutrinos) has the 3 accidental global symmetries L_e, L_μ, L_τ. Gauge them?
- Anomalies (kill renormalizability)...



- Turns out only anomaly-free linear combinations are $L_e - L_\mu$, $L_e - L_\tau$ and $L_\mu - L_\tau$, can gauge *one* of them.

$L_e - L_{\mu,\tau}$

- Strong constraints on $L_e - L_{\mu,\tau}$ from equivalence principle, atomic physics, e^+e^--colliders, neutrino-interactions...
- $L_\mu - L_\tau$ does not couple to first generation particles, less constrained.
- Not the usual motivation for Z', no GUTs, no strings
- Coupling constant g' free parameter

Neutrinos

- Neutrino oscillations demand particles beyond SM, e.g. righthanded neutrinos. Can find $U(1)_{L_\mu - L_\tau}$ charges for them to keep the model anomaly free.
- Unbroken symmetry gives diagonal Dirac mass matrices and Majorana matrices of the form

$$\mathcal{M}_R = \begin{pmatrix} X & 0 & 0 \\ 0 & 0 & Y \\ 0 & Y & 0 \end{pmatrix}$$

  Quasi-degenerate, wrong θ_{12}.
- Need to break the $U(1)_{L_\mu - L_\tau}$ symmetry $\Rightarrow$ massive Z'

Neutrinos II

$$\mathcal{M}_\nu = \begin{pmatrix} X & 0 & 0 \\ 0 & 0 & Y \\ 0 & Y & 0 \end{pmatrix}$$

- Only two texture-zeros allowed, need additional entries via VEVs or radiatively [arXiv:*hep-ph/0605231*]
- Depends strongly on the Higgs sector, i.e. break the $U(1)_{L_\mu - L_\tau}$ via VEV of a scalar singlet, doublet, triplet...
- Complicated Higgs-sector, e.g. CP-odd scalars, charged Higgs, light pseudo-Goldstone bosons, LFV...
- Was also used to explain PAMELA positron excess [arXiv:*0811.1646*]

Lagrangian

- Most general Lagrangian for an extra $U(1)'$:

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{Z'} + \mathcal{L}_{\text{mix}}$$

- relevant part of the standard model Lagrangian is

$$\mathcal{L}_{\text{SM}} = -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{W}^a_{\mu\nu}\hat{W}^{a\mu\nu} + \frac{1}{2}\hat{M}_Z^2\hat{Z}_\mu\hat{Z}^\mu$$

- Z' part in our case is

$$\mathcal{L}_{Z'} = -\frac{1}{4}\hat{Z}'_{\mu\nu}\hat{Z}'^{\mu\nu} + \frac{1}{2}\hat{M}'^2_Z\hat{Z}'_\mu\hat{Z}'^\mu - \hat{g}' j'^\mu Z'_\mu$$
$$j'^\mu = \bar{\mu}\gamma^\mu\mu + \bar{\nu}_\mu\gamma^\mu P_L\nu_\mu - \bar{\tau}\gamma^\mu\tau - \bar{\nu}_\tau\gamma^\mu P_L\nu_\tau$$

- kinetic and mass-mixing terms are

$$\mathcal{L}_{\text{mix}} = -\frac{\sin\chi}{2}\hat{Z}'^{\mu\nu}\hat{B}_{\mu\nu} + \delta\hat{M}^2\hat{Z}'_\mu\hat{Z}^\mu$$

Diagonalization

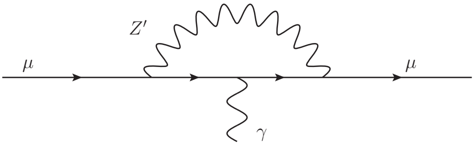
- Diagonalization of the kinetic (mixing angle χ) and mass terms (mixing angle ξ) gives a massless photon, two massive bosons Z_1 (mostly the classical Z_{SM}) and Z_2 (mostly Z')
- Z' couples to first generation particles with the strength of the mixing angles
- $Z - Z'$-mixing constrained by the ρ-parameter

$$\rho = \left(\frac{M_W}{M_{Z_1} c_W} \right)^2$$

- Z_1-coupling to leptons becomes slightly non-universal

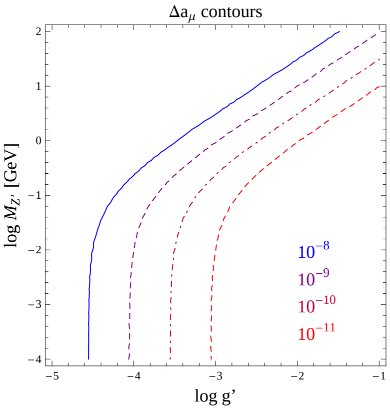
Higher-order constraints

- Even in unmixed case: Z'-effects in loops, e.g. magnetic moment of muon



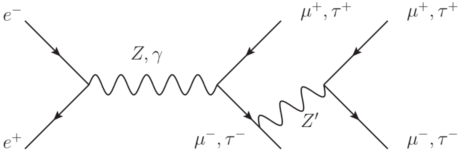
- Can explain the difference between theoretic and experimental value [arXiv:*hep-ph/0110146*]

Magnetic moment



Direct detection

- Final state muons can radiate Z'



- Clean 4μ final state with $\mu^-\mu^+$-clustering around the Z' mass
- Small cross section $\sim \mathcal{O}(0.1\,\mathrm{pb})$, high-luminosity measurements at LEP around $\sqrt{s} \approx 90\,\mathrm{GeV}$ expected and found 20 such $\mu^-\mu^+\mu^-\mu^+$ events via SM particles
- Most promising detection possibility: s-channel in a future muon-collider

Ultralight Z'

- Z' with mass $\sim 1/\text{A.U.}$ leads to leptonic "fifth force"
- Induces a long-range force between neutrons:

$$V_{Z'}(r) \sim \xi^2 \, \frac{N_1 N_2}{r}$$

$\Rightarrow$ Constraints from Equivalence Principle (EP) on the mixing angles $\xi < 10^{-24}$

- Big Bang Nucleosynthesis (extra relativistic d.o.f.): Equilibrium below $T = 1\,\mathrm{MeV}$ [arXiv:*astro-ph/9610205*]:

$$g' < 10^{-5}$$

- Similar constraints from additional Z'-luminosity of SN1987a [arXiv:*hep-ph/9708465*]
- Can still affect neutrino oscillations (mainly the atmospheric sector)

Neutrino oscillations

- Mixing induces a neutron-generated potential for $\nu_{\mu,\tau}$, e.g. neutrons in Sun give on Earths surface:

$$V \sim 4 \times 10^{-14}\,\mathrm{eV}\ \frac{g'\xi}{10^{-50}}$$

- neutrino propagation gets changed to $(A = 2E\sqrt{2}G_F n_e)$

$$i\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{\nu} = \frac{1}{2E}\left[UM_\nu^2U^\dagger + \begin{pmatrix} A & 0 & 0 \\ 0 & 2EV & 0 \\ 0 & 0 & -2EV \end{pmatrix}\right]\boldsymbol{\nu}$$

- similar to non-standard neutrino interactions (NSI), but long- instead of short-ranged
- limits the product $g'\xi < 10^{-50}$

Neutrino oscillations II

- In 2-flavor framework

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta_V \ \sin^2 \frac{\Delta m_V^2}{4\,E} L$$

with

$$\sin^2 2\theta_V = \frac{\sin^2 2\theta}{1 - 4\,\eta\ \cos 2\theta + 4\,\eta^2}\,,$$
$$\Delta m_V^2 = \Delta m^2 \sqrt{1 - 4\,\eta\ \cos 2\theta + 4\,\eta^2}$$

and $\eta \equiv \frac{2\,E\,V}{\Delta m^2}$.

- V changes sign for anti-neutrinos $\Rightarrow$ $\nu_{\mu,\tau}$ and $\bar{\nu}_{\mu,\tau}$ oscillate differently
- Explains MINOS-anomaly?

Conclusion

- Weird model
- Mostly limits on the "mixing parameters" ξ, χ (the coupling to first generation particles)
- Easily verifiable at pure muon experiments:
  - Muonium
  - Muon collider