2nd TDLI Mini-Workshop on "New Physics at the Tera Scale"

B-L SOLUTION TO THE MUON G-2 PUZZLE

Based on 1905.11018, by ZK &, Yoshihiro Shigekami

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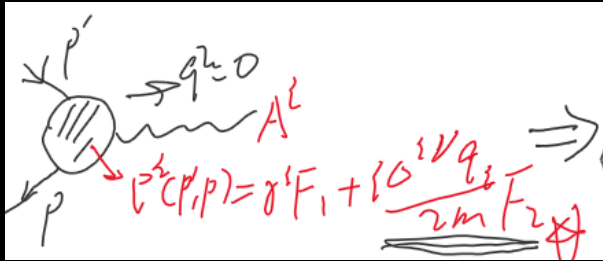
Outline & pre-summary

- A short review on the longstanding $(g-2)_\mu$ puzzle & its solutions
- 2nd & 3rd flavored $B-L$ force offers a solution, quite similar but maybe a better solution than the local $L_\mu - L_\tau$ scheme
- Not trivial to build a realistic model to reconcile $(g-2)_\mu$ with the down quark sector FCNC constraints from K & B
- Top FCNC decay is an important signal to test and distinguish the model from other solutions

$(g-2)_\mu$: A long standing puzzle

- The muon magnetic anomaly as a test of SM

Electron/muon magnetic momentum



$$\Rightarrow \langle \boldsymbol{\mu} \rangle = \frac{e}{m}[F_1(0)+F_2(0)]\xi'^\dagger \frac{\boldsymbol{\sigma}}{2}\xi. = g\left(\frac{e}{2m}\right)\mathbf{S} \Rightarrow g = 2F_1+2F_2 = 1+2F_2$$

- ☞ The Lande g-factor deviating from 2 was a test of QED
- ☞ Now it services as **a probe to new physics from loops**
- ☞ New physics effect may be encoded in the *d=5* operator

$$\delta\mathcal{L}_{\rm eff}^{\rm AMM} = -\frac{\delta g}{2}\frac{e}{4m}\left\{\bar\psi_L(x)\,\sigma^{\mu\nu}F_{\mu\nu}(x)\,\psi_R(x) + \bar\psi_R(x)\,\sigma^{\mu\nu}F_{\mu\nu}(x)\,\psi_L(x)\right\}$$

But this is not generically true since new particles may be even lighter than muon, says the axion-like particles

$(g-2)_\mu$: A long standing puzzle

- $(g-2)_\mu$: a robust anomaly

SM prediction: fighting with the hadronic contributions

$$a_\mu^{\rm SM} = (11\ 659\ 182.04 \pm 3.56) \times 10^{-10}$$

A. Keshavarzi, D. Nomura and T. Teubner, PRD (2018).

Experimental measurements on $(g-2)_\mu$

- The early work since 1960s in Columbia University: $\mu \sim e$
- Muon storage ring since CERN
- Deviation established by a series of measurements in BNL (2002,2004,2006), now a 3.7σ deviation:

$$a_\mu^{\rm exp} = (11\ 659\ 209.1 \pm 5.4_{\rm stat} \pm 3.3_{\rm sys}) \times 10^{-10} \qquad \Delta a_\mu = (27.06 \pm 7.26) \times 10^{-10}$$

C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update.

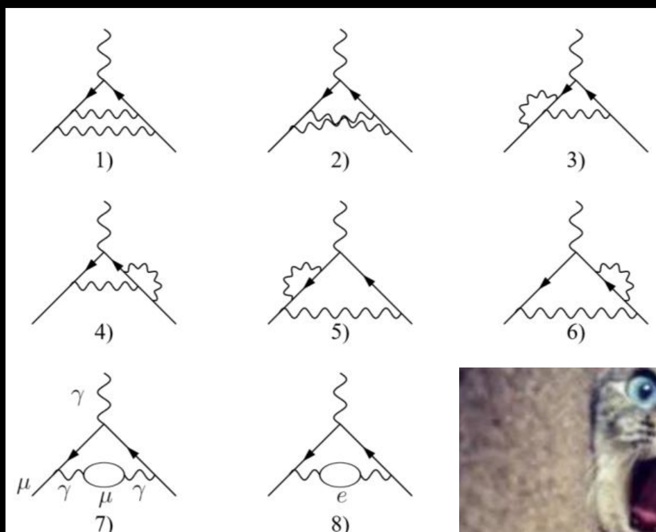
future programs towards $\sim 7\sigma$

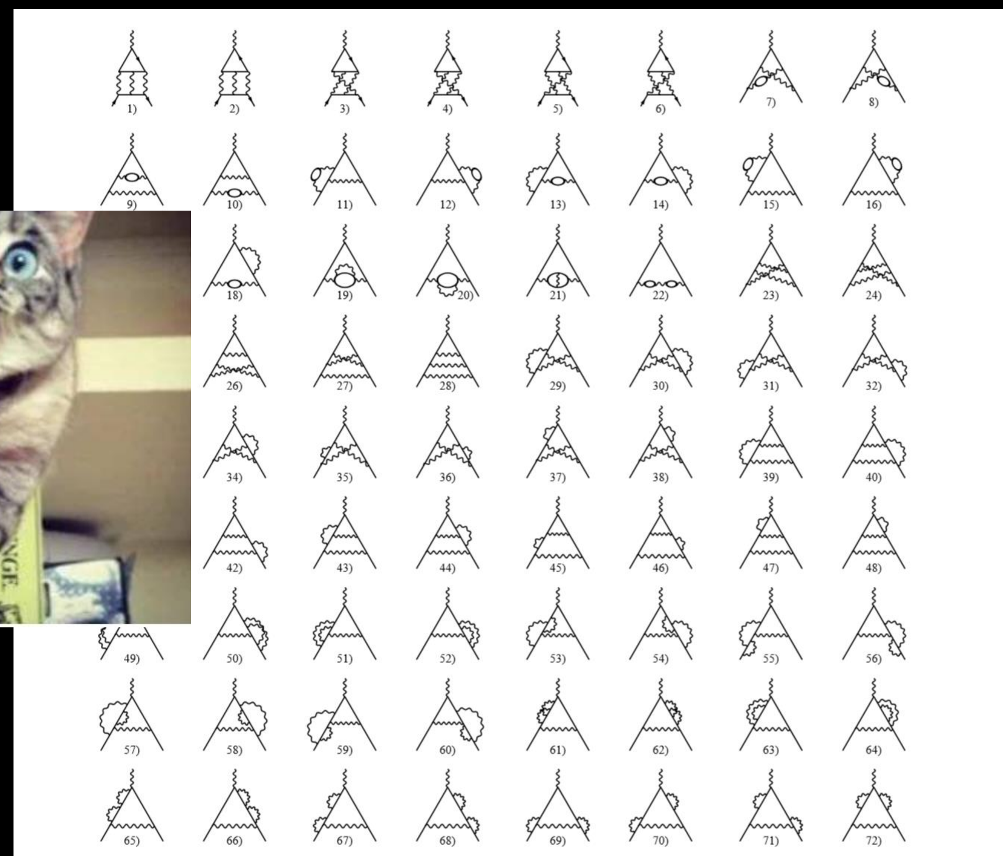
- Fermilab (E989) — J. Grange et al. [Muon g-2 Collaboration], arXiv:1501.06858
- Proposed J-PARC experiment

T. Mibe [J-PARC g-2 Collaboration], Chin. Phys. C34745 (2010).

$(g-2)_\mu$: A long standing puzzle

- SM of $(g-2)_\mu$: show just to salute





Cheap solutions to the $(g-2)_\mu$ puzzle

- Weak scale charged loop solution

  Via new weak scale charged particles weakly coupling to the muon sector

  ☞ E.g., the sneutrino-chargino loop in supersymmetry

  ☞ Connection to the leptonic dark matter?

  E.g., Jin min Yang's talk

- Mildly light neutral particle solution

  A light CP-even spin-0 at one-loop

  A light CP-odd spin-0 at **two-loop** (Zee-Babu)

  ☞ E.g., in the leptonic two-Higgs doublet model

  Eung Jin Chun,ZK, Michihisa Takeuchi and Yue-Lin Sming Tsai, JHEP (2015)

- Very light dark neutral particle (μ –force) but very weakly coupling solution

  Initiated by M. Pospelov, Phys. Rev. D 80, 095002 (2009)

Cheap solutions to the $(g-2)_\mu$ puzzle

- Muonic force solution: a new gauge sector?

A weak scale Z' coupling to muon is ruled out

☞ The minimal coupling for an **electron-phobic Z'**

$$-\mathcal{L}^{l}_{Z'} = -g_{B-L}(\bar{\mu}\gamma^\mu\mu + \bar{\tau}\gamma^\mu\tau + \bar{\nu}_\mu\gamma^\mu\nu_\mu + \bar{\nu}_\tau\gamma^\mu\nu_\tau)Z'_\mu,$$

☞ **CCFR Neutrino trident production: rule out a heavy $M_{Z'} \gtrsim 0.4\mathrm{GeV}$**

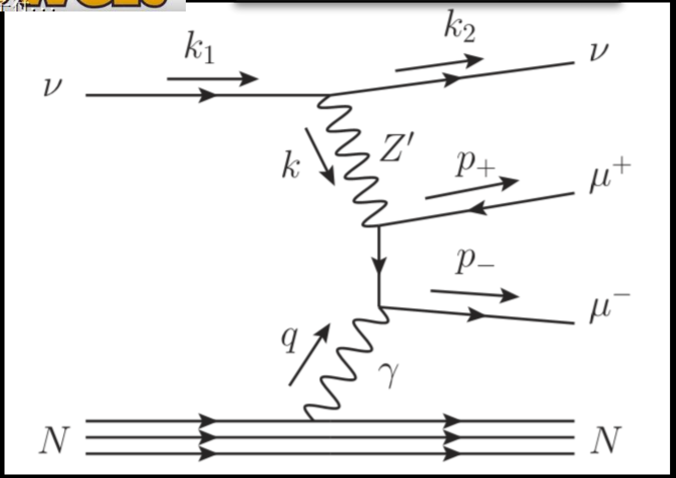
W. Altmannshofer, S. Gori, M. Pospelov and I. Yavin, PRL (2014)

☞ BaBar 4μ search $M_{Z'} \gtrsim 2m_\mu$

$$e^+e^- \to \mu^+\mu^- Z' \text{ followed by } Z' \to \mu^+\mu^-$$

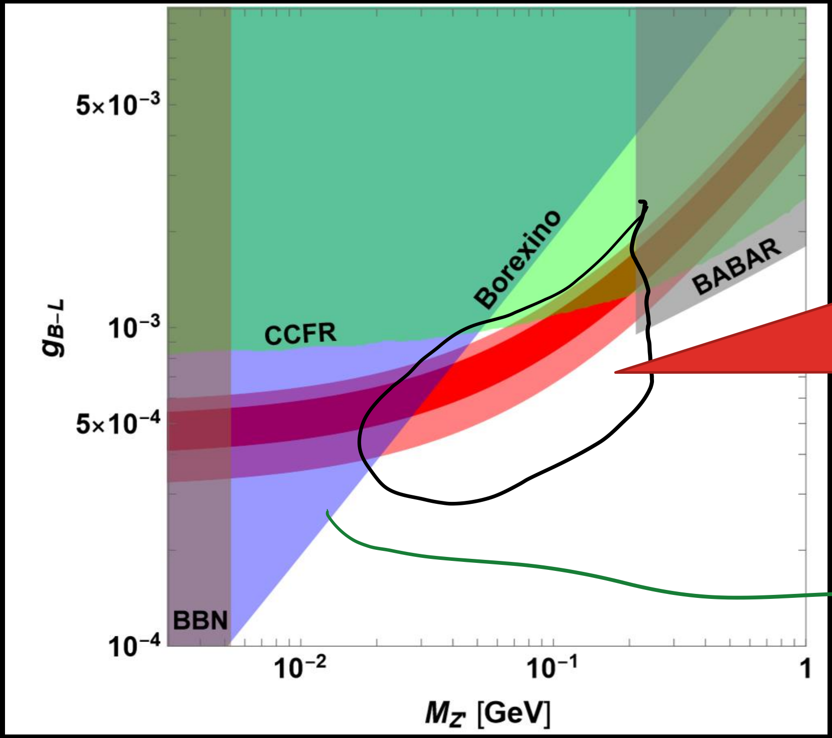
☞ BBN gives $M_{Z'} \gtrsim 1\mathrm{MeV}$

- Assuming a ordinary thermal history for Z'
- it contributes to effective relativistic degree of freedom
- Might be evaded?



Cheap solutions to the $(g-2)_\mu$ puzzle

- Leaving a Z' within the sub-GeV corner



- If not electron-phobic, then there is $e\nu_\mu \to e\nu_\mu$
- If there is not suppressed coupling to electron, the Borexino experiment will close this window

X.-G. He, G. C. Joshi, H. Lew and R. R. Volkas, Phys. Rev. D 43, 22 (1991); Phys. Rev. D 44, 2118 (1991).

- The well-known example: gauged $L_\mu - L_\tau$
- New competitor: local $B-L$ for 2nd & 3rd families

A $(B\!-\!L)_{\mu\tau}$ dark force

- Why such an idea?

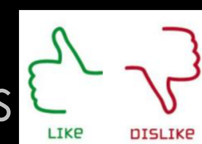
Up-front investments to the local B-L extensions

Gauging $B-L$ is an elegant idea for $m_v \neq 0$

☞ In this sense it is better than the local $L_\mu - L_\tau$

Little seesaw: Two generations is enough?

☞ Enough for neutrino masses but not mixings



electron-phobic Z'!

New members in the model

☞ 2 RHNS to cancel anomaly

☞ New Higgs to break $(B\!-\!L)_{\mu\tau}$

☞ Flavons to generate mixings

☞ $i = 2,3$

	spin	$SU(2)_L$	$U(1)_Y$	$(B-L)_{\mu\tau}$
Q_i	1/2	2	1/6	1/3
$u_{R,i}$	1/2	1	2/3	1/3
$d_{R,i}$	1/2	1	−1/3	1/3
U_L	1/2	1	2/3	1/3
U_R	1/2	1	2/3	1/3
$\mathcal{F}$	0	1	0	1/3
L_i	1/2	2	−1/2	−1
$e_{R,i}$	1/2	1	−1	−1
$N_{R,i}$	1/2	1	0	−1
H	0	2	1/2	0
Φ	0	1	0	2

A $(B-L)_{\mu\tau}$ dark force

- Knock CKM & PMNS together by flavons

Ways to the CKM pattern!!!

☞ Only 2nd & 3rd are mixing owing to the flavorful $B-L$

☞ 12 /13 mixings plan A: a Higgs doublet flavon $H_{\mu\tau}$

$$-\mathcal{L}_Y \supset \widetilde{Y}^u_{1i}\overline{Q}_1\widetilde{H}_{\mu\tau}u_{R,i} + \widetilde{Y}^d_{i1}\overline{Q}_i H_{\mu\tau} d_{R,1} + h.c.,$$

$$m_u^0 = \frac{v_h}{\sqrt{2}}\begin{pmatrix} Y^u_{11} & \widetilde{Y}^u_{12}\sqrt{r_{\mu\tau}} & \widetilde{Y}^u_{13}\sqrt{r_{\mu\tau}} \\ 0 & Y^u_{22} & Y^u_{23} \\ 0 & Y^u_{32} & Y^u_{33} \end{pmatrix}, \quad m_d^0 = \frac{v_h}{\sqrt{2}}\begin{pmatrix} Y^d_{11} & 0 & 0 \\ \widetilde{Y}^d_{21}\sqrt{r_{\mu\tau}} & Y^d_{22} & Y^d_{23} \\ \widetilde{Y}^d_{31}\sqrt{r_{\mu\tau}} & Y^d_{32} & Y^d_{33} \end{pmatrix},$$

- Im_d^0 and the current $Z'_\mu \bar{d}_i \gamma^\mu d_i$ ($i = 2,3$) cannot be diagonalized simultaneously, giving rise to down quark FCNC!!!
- K & B rare decay **CLEARLY RULE OUT** the $(g-2)_\mu$ solution by Z'

$$\Delta\mathrm{BR}(B^+ \to K^+\nu\bar{\nu})_{\rm exp} = (0.35^{+0.60}_{-0.15}) \times 10^{-5},$$
$$\mathrm{BR}(K^+ \to \pi^+ Z')_{\rm exp} < \mathcal{O}(10^{-10}) \quad (\text{when } M_{Z'} \simeq \mathcal{O}(10)\ \mathrm{MeV})$$
$$\mathrm{BR}(K_L \to \pi^0\nu\bar{\nu})_{\rm exp} < 3.0 \times 10^{-9}.$$

$$|(U_d)^*_{d'd}(U_d)_{d's}| < 6.2 \times 10^{-10}$$

A $(B\text{–}L)_{\mu\tau}$ dark force

- Knock CKM & PMNS together by flavons

Ways to the CKM pattern!!!

☞ 12 /13 mixings plan B: by virtue of vector-like quark flavons, choosing

$$-\mathcal{L}_U = M_U \overline{U}_L U_R + M_{Ui} \overline{U}_L u_{R,i} + \lambda_1 \overline{U}_L u_{R,1} \mathcal{F} + \lambda_i \overline{Q}_i \widetilde{H} U_R + h.c.$$

$$m_u^0 = \frac{v_h}{\sqrt{2}} \begin{pmatrix} Y_{11}^u & y_{12}^u v_f/\Lambda & y_{13}^u v_f/\Lambda \\ y_{21}^u v_f/\Lambda & Y_{22}^u & Y_{23}^u \\ y_{31}^u v_f/\Lambda & Y_{32}^u & Y_{33}^u \end{pmatrix}, \quad m_d^0 = \frac{v_h}{\sqrt{2}} \begin{pmatrix} Y_{11}^d & 0 & 0 \\ 0 & Y_{22}^d & Y_{23}^d \\ 0 & Y_{32}^d & Y_{33}^d \end{pmatrix}$$

- Block structure, m_d^0 and $Z'_\mu \bar{d}_i \gamma^\mu d_i$ is diagonalized simultaneously
- Thus no ds & db mixing in the down quark sector FCNC!!
- **quantum number selected pattern**

Not the end, PMNS also requires flavons

☞ The 2nd & 3rd flavored B-L give you the correct neutrino mass but not the correct mixing

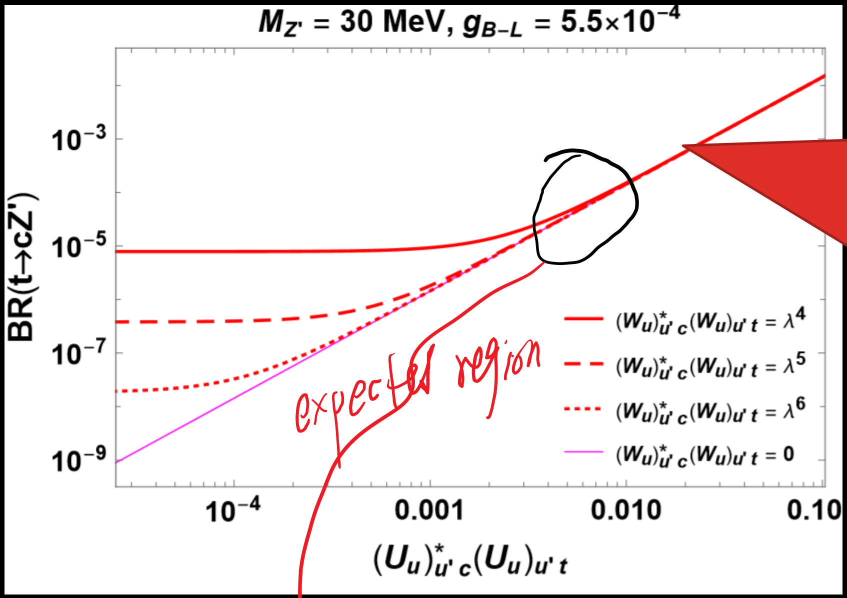
A $(B-L)_{\mu\tau}$ dark force

- Leave a hint in top FCNC decay?

Up quark sector FCNC generically not suppressed

☞ No strong constraints from the first two families

☞ One promising channel $t \to cZ'(\to \nu\bar{\nu})$



$(U_u)_{u't} \lesssim \lambda^3$ $\quad$ $(U_u)_{u'u} \sim 1.$

- No meaningful constraints on such an invisible Z' yet
- For demonstration, if $Z' \to \mu\bar{\mu}$, then inferred from $t \to cz$

$$\mathcal{B}(t \to cZ') \lesssim \begin{cases} 10^{-4} & (\text{“CMS” Run 1}), \\ 5 \times 10^{-5} & (\text{“CMS” } 300 \text{ fb}^{-1}), \\ 2 \times 10^{-5} & (\text{“CMS” } 3000 \text{ fb}^{-1}) \end{cases}$$

- CLIC may reach a sensitivity at the level ~ 10^{-4} (380GeV,1/ab)

Top-Quark Physics at the CLIC Electron-Positron Linear Collider, CLICdp collaboration 1807.02441

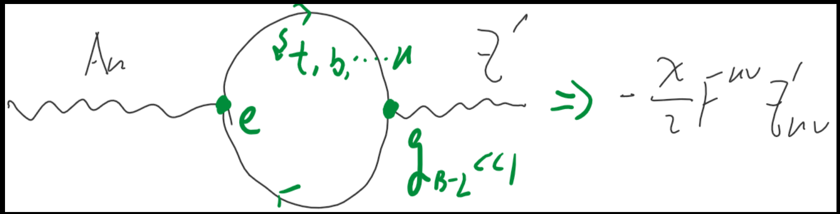
A $(B-L)_{\mu\tau}$ dark force

- Maybe a sooner test from SHiP

Z' recouples to electron at loop

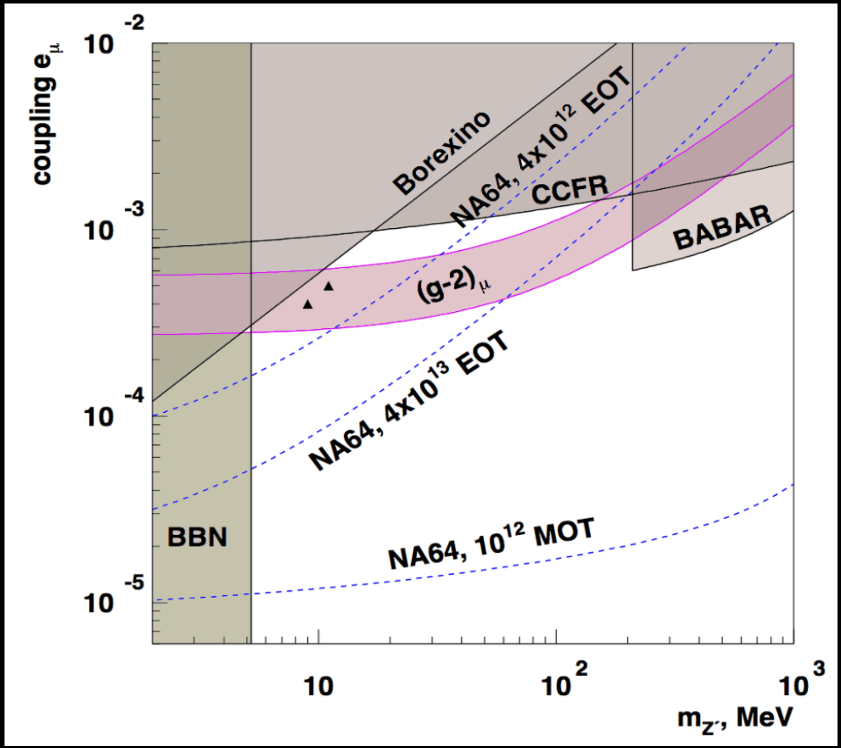
☞ Many fermions are charged both under QED & $(B-L)_{\mu\tau}$

☞ if there is no fine cancelation from tree and loop



$$\chi = -\frac{e g_{B-L}}{18\pi^2} \ln\left(\frac{m_c^2 m_t^2 m_\mu^3 m_\tau^3}{m_s m_b M_U^8}\right)$$

☞ many experiments can search for the light dark Z' and close the window



Summary

- Neutrino mass and the $(g-2)_\mu$ solution are nicely unified in the 2^{nd} & 3^{rd} flavored $B-L$ force model
- We build a realistic model to reconcile $(g-2)_\mu$ with the down quark sector FCNC constraints from K & B
- Top FCNC decay is an important signal to test and distinguish the model from other solutions
- Thank you for your attention!!