Physics Letters B 820 (2021) 136585

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Leptophilic $U(1)$ massive vector bosons from large extra dimensions

Luis A. Anchordoqui [a,b,c,*], Ignatios Antoniadis [d,e], Xing Huang [f,g,h], Dieter Lüst [i,j], Tomasz R. Taylor [k]

[a] Department of Physics and Astronomy, Lehman College, City University of New York, NY 10468, USA
[b] Department of Physics, Graduate Center, City University of New York, NY 10016, USA
[c] Department of Astrophysics, American Museum of Natural History, NY 10024, USA
[d] Laboratoire de Physique Théorique et Hautes Énergies - LPTHE Sorbonne Université, CNRS, 4 Place Jussieu, 75005 Paris, France
[e] Institute for Theoretical Physics, KU Leuven, Celestijnenlaan 200D, B-3001 Leuven, Belgium
[f] Institute of Modern Physics, Northwest University, Xi'an 710069, China
[g] NSFC-SPTP Peng Huanwu Center for Fundamental Theory, Xi'an 710127, China
[h] Shaanxi Key Laboratory for Theoretical Physics Frontiers, Xi'an 710069, China
[i] Max–Planck–Institut für Physik, Werner–Heisenberg–Institut, 80805 München, Germany
[j] Arnold Sommerfeld Center for Theoretical Physics Ludwig-Maximilians-Universität München, 80333 München, Germany
[k] Department of Physics, Northeastern University, Boston, MA 02115, USA

ARTICLE INFO

Article history:
Received 27 May 2021
Received in revised form 15 July 2021
Accepted 11 August 2021
Available online 17 August 2021
Editor: A. Volovich

ABSTRACT

We demonstrate that the discrepancy between the anomalous magnetic moment measured at BNL and Fermilab and the Standard Model prediction could be explained within the context of low-scale gravity and large extra-dimensions. The dominant contribution to $(g-2)_\mu$ originates in Kaluza-Klein (KK) excitations (of the lepton gauge boson) which do not mix with quarks (to lowest order) and therefore can be quite light avoiding LHC constraints. We show that the KK contribution to $(g-2)_\mu$ is universal with the string scale entering as an effective cutoff. The KK tower provides a unequivocal distinctive signal which will be within reach of the future muon smasher.

© 2021 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP³.

Low scale gravity and large extra dimensions offer a genuine solution to the gauge hierarchy problem [1,2]. Within these models one has to address the problem of baryon B and lepton L number violation by higher dimensional operators suppressed only by the low string scale M_s. Intersecting D-brane models offer a way out by gauging these symmetries [3–7]. Since the B and L gauge bosons are anomalous they gain masses through a generalization of the Green-Schwarz (GS) anomaly cancellation [8–11] giving rise to perturbative global symmetries broken only by non-perturbative effects that are suppressed exponentially by the string/gauge coupling. The resulting gauge bosons form in general linear combinations of the various abelian gauge factors orthogonal to the hypercharge combination, that couple to both quark and leptons. However, the Kaluza-Klein (KK) excitations do not mix (to lowest order) and thus those of L couple only to leptons. Such modes can be quite light because LHC constraints are weak but can provide a sizable contribution to the anomalous magnetic moment of the muon $a_\mu = (g-2)_\mu/2$.

TeV-scale D-brane string compactifications could then provide an innovative framework to explain the extant tension between the Standard Model (SM) prediction of a_μ and experiment. Very recently, the Muon $g-2$ Experiment at Fermilab reported a measurement reading $a_\mu^{\rm FNAL} = 116592040(54) \times 10^{-11}$ [12], which is larger than the SM prediction $a_\mu^{\rm SM} = 116591810(43) \times 10^{-11}$ in which contributions from QED, QCD, and electroweak interactions are taken into account with highest precision [13]. This leads to $a_\mu^{\rm FNAL} - a_\mu^{\rm SM} = (230 \pm 69) \times 10^{-11}$, which corresponds to a 3.2σ discrepancy. Because the Fermilab observation is compatible with the long-standing discrepancy from the E821 experiment at BNL [14], the overall deviation from the SM central value,

$$\Delta a_\mu^{\rm exp} \equiv a_\mu^{\rm FNAL+BNL} - a_\mu^{\rm SM} = (251 \pm 59) \times 10^{-11}\,, \tag{1}$$

strengthens the significance to 4.2σ [12].[1] Even though the discrepancy is not statistical significant yet, it is interesting to en-

* Corresponding author.
E-mail address: luis.anchordoqui@gmail.com (L.A. Anchordoqui).

[1] We note in passing that the SM prediction estimated by the latest lattice QCD calculations, $a_\mu^{\rm SM,lattice} = 11659195163(58) \times 10^{-11}$, has a larger uncertainty and brings the prediction closer to the experimental value, $a_\mu^{\rm FNAL+BNL} - a_\mu^{\rm SM,lattice} = 109(71) \times 10^{-11}$, yielding only a 1.6 σ effect [15].

https://doi.org/10.1016/j.physletb.2021.136585
0370-2693/© 2021 The Author(s). Published by Elsevier B.V. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0/). Funded by SCOAP³.

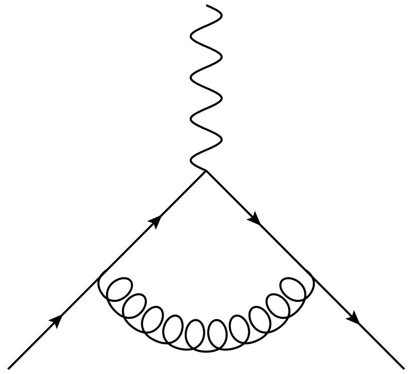

Fig. 1. KK gauge boson (double wavy line) contribution to muon's anomalous magnetic moment.

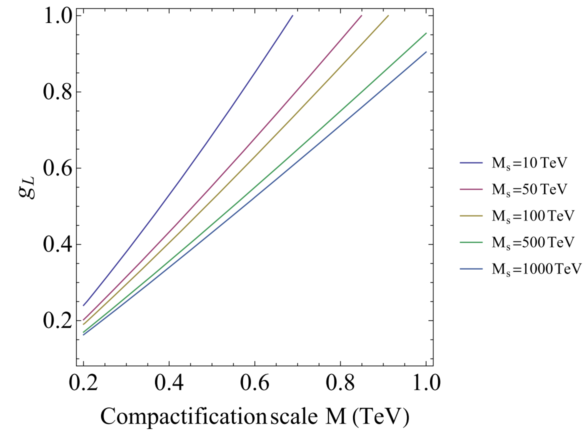

Fig. 2. Contours of constant $\Delta a_\mu^{\rm exp}$ for different values of M_s.

tertain the possibility that it corresponds to a real signal of new physics. In this Letter we calculate the massive vector boson contribution to $g-2$ from KK excitations of L and we show that it is *universal* and can accommodate the $\Delta a_\mu^{\rm exp}$ discrepancy of (1).

At the leading order in the $U(1)_L$ coupling constant g_L, the contribution of a massive vector boson to lepton's $g-2$ originates from the vertex correction shown in Fig. 1. Note that KK momentum is not conserved in lepton gauge boson vertices since leptons are localized in brane intersections. Fig. 1 shows the same diagram that yields the famous α/π in QED, but with the virtual photon replaced by a massive vector boson. The fastest way to compute it is to use the massive propagator in unitary gauge,

$$D^{\mu\nu}(k) = \frac{-i}{k^2 - M^2}\left(g^{\mu\nu} - \frac{k^\mu k^\mu}{M^2}\right), \tag{2}$$

and follow a textbook, for example Ref. [16]. It is easy to see that the longitudinal part of the propagator (second term in Eq. (2)) does not contribute to the magnetic moment. The only difference between the first term and the photon propagator in Feynman gauge is M^2 in the denominator which leads to a slight modification of the integral over Feynman parameters. In the limit of $M \gg m$, one obtains

$$\Delta a_\mu = \frac{(g-2)_\mu}{2} = \frac{1}{3}\frac{\alpha_L}{\pi}\frac{m^2}{M^2}\,, \tag{3}$$

where we neglected terms of order $(m/M)^4$ and m is the muon mass. Note that this is a *positive* correction that brings a_μ closer to experimental data.

The masses of KK gauge bosons are labelled by integer vectors $\vec{n}$, with $M^2(\vec{n}) = |\vec{n}|^2 M^2$, where M is the compactification scale. For $M \ll M_s$ the couplings $\alpha_L(\vec{n})$ depend very mildly on $\vec{n}$ when $|\vec{n}|$ is small [17]. They are approximately 1 until $|\vec{n}| \approx M_s/M$ and then exponentially suppressed when $|\vec{n}| \gg M_s/M$. They are given by a Gaussian form $\alpha_L(\vec{n}) = \delta^{-\vec{n}^2 M^2/M_s^2}$ with $\delta < 1$ a model dependent constant. In the case of one extra dimension

$$\Delta a_\mu = \sum_n \frac{1}{3}\frac{\alpha_L(n)}{\pi}\frac{m^2}{n^2 M^2} \approx \frac{\alpha_L \pi}{18}\frac{m^2}{M^2}\,. \tag{4}$$

In the case of two extra dimensions, the exponential suppression of $\alpha_L(\vec{n})$ at large $|\vec{n}|$ is crucial for regulating the logarithmic divergence of the sum:

$$\Delta a_\mu = \sum_{\vec{n}} \frac{1}{3}\frac{\alpha_L(\vec{n})}{\pi}\frac{m^2}{|\vec{n}|^2 M^2} \approx \frac{2\alpha_L}{3}\frac{m^2}{M^2}\,\ln\left(\frac{M_s}{M}\right). \tag{5}$$

Here, α_L is the coupling of the lightest KK excitation.

To develop some sense for the orders of magnitude involved, we recall that direct production at LEP provides the best bound on KK couplings and masses. The agreement between the LEP-II measurements and the SM predictions implies that either $g_L \lesssim 10^{-2}$, or else $M > 209$ GeV, the maximum energy of LEP-II [18]. In Fig. 2 we show contours of constant $\Delta a_\mu^{\rm exp}$ in the $g_L - M$ plane for different values of the string scale. We see that there is a large range of masses and couplings that can accommodate the Fermilab result. A point worth noting at this juncture is that the KK contribution to $(g-2)_\mu$ is universal, with M_s entering as an effective cutoff.

There are two different classes of D-brane constructs that can realize the tower of KK modes. On the one hand, we can envision that L is part of the hypercharge (thus its gauge coupling α_L cannot be very small). One can then try to use one of the orthogonal to the hypercharge combinations for explaining the $(g-2)_\mu$ discrepancy and make it leptophilic to avoid the LHC bounds. It turns out that this cannot be done because the corresponding $U(1)$ gauge coupling becomes strong. Indeed, the 4 stack model thoroughly analyzed in [19], with gauge group $U(3)_a \times Sp(1)_b \times U(1)_c \times U(1)_d$, typifies this class. Contact with gauge structures at TeV energies is achieved by a field rotation to couple diagonally to hypercharge Y. Two of the Euler angles (ψ, θ, ϕ) are determined by this rotation. The gauge couplings are related to g_Y by

$$\frac{1}{(6g'_a)^2} + \frac{1}{(2g'_c)^2} + \frac{1}{(2g'_d)^2} = \frac{1}{g_Y^2}\,, \tag{6}$$

and the relation for $U(N)$ unification, $g'_N = g_N/\sqrt{2N}$, holds only at M_s because the $U(1)$ couplings $(g'_a,\, g'_c,\, g'_d)$ run differently from the non-abelian $SU(3)$ (g_a) and $SU(2) \equiv Sp(1)$ (g_b) [20]. The zero-mode of the anomalous $U(1)$, hereafter Z', gains a mass via the GS mechanism by absorbing an axionic field from the R-R (Ramond) closed string sector. To get as much contribution to a_μ as possible without violating the LHC bounds [21,22], it is natural to consider a leptophilic (in our case meaning large $g_L \equiv g'_c$) Z' [23]. Next, we compare with the LHC data considering the resonant production cross section of $\sigma(pp \to Z' \to \ell\ell)$. Under the narrow width approximation, the cross section can be written in the form of $c_u w_u + c_d w_d$, where w_u, w_d are given by model-independent parton distribution functions [24]. The coupling of Z' with up and down quarks (assuming same coupling to three families) are encoded in c_u, c_d. More precisely, for a generic coupling between Z' and fermion f

$$Z'_\mu \gamma^\mu (\bar{f}_L \epsilon_L^f f_L + \bar{f}_R \epsilon_R^f f_R)\,, \tag{7}$$

the coefficients c_u and c_d take the following form

$$c_f = (\epsilon_L^{f\,2} + \epsilon_R^{f\,2}) \mathrm{Br}(\ell^+\ell^-) \,. \tag{8}$$

We compute the branching faction $\mathrm{Br}(\ell^+\ell^-)$ by including only the decay channels to leptons and quarks. The total decay rate is given by

$$\Gamma_{Z'} = \frac{1}{24\pi} M_{Z'} \left[9 \sum_{q=u,d} (\epsilon_L^{q\,2} + \epsilon_R^{q\,2}) + 3 \sum_{\ell=e,\nu} (\epsilon_L^{\ell\,2} + \epsilon_R^{\ell\,2}) \right] . \tag{9}$$

Due to the constraint (6), there are two free parameters (for a given string scale M_s): ϕ and $g'_d(M_s)$. Setting the mass of Z' to 2 TeV, we then search over the parameter space to get the smallest possible values of c_u, c_d. For simplicity, the combination of $\sqrt{c_u^2 + c_d^2}$ is considered. We find that the optimal value of ϕ generally suppresses the couplings to left-handed quarks and the remaining couplings to the right-handed quarks are controlled by g'_d. In the best case scenario, $g'_c(M_s)$ is set to 2π at M_s (with $10 \lesssim M_s/\mathrm{TeV} \lesssim 10^3$), the corresponding cross section (or rather $\sqrt{c_u^2 + c_d^2} \sim 8.4 \times 10^{-5}$) is roughly 2 percent of that given by the sequential standard model boson $Z'_{\rm SSM}$ [25], saturating the LHC limit [22]. We note that the branching fraction to leptons is close to 1 due to the small coupling to quarks. The signal can be further reduced by including other decay channels. Moreover, the largest possible $g'_c(M_s)$ also gives the most contribution to a_μ. Such a Z' boson gives $a_\mu = 9.9 \times 10^{-11}$ [19], which is much smaller than the pre-LHC estimate of Ref. [26] and it is not enough to explain the observed discrepancy. The second anomalous $U(1)$ should be much heavier to avoid the LHC bound and its contribution to a_μ is negligible. To accommodate the Fermilab data one can advocate the violation of lepton flavor universality [23]. Alternatively, as we have shown in Fig. 2, the Fermilab/BNL data can be interpreted as evidence for *massive vector boson contributions to* $g-2$ *from KK excitations of the* $U(1)_c$. Note that in contrary to the gauge boson 0-mode which acquires a mass from the anomaly, the masses of KK modes originate from the internal component(s) of the higher dimensional gauge field.

On the other hand, we can envision that L is not part of the hypercharge. If this were the case, the KK tower and even its (anomalous) zero-mode would be completely unconstrained. The generic features of the D-brane constructs (with more than 4 stacks of D-branes) that can realize this class of models can be summarized as follows:

- the lepton doublet should lie on the intersection of the weak $U(2)_w$ and $U(1)_L$, so that the Abelian charge Q_L participates in the hypercharge Y but not L;
- the lepton l^c should lie on an intersection of a $U(1)$ that participates in Y and $U(1)_L$ so that has opposite lepton charge from l;
- the quarks should not see $U(1)_L$;
- $U(1)_L$ can even be in the bulk (or part of it) with no important accelerator constraints.

In summary, we have shown that the exchange of KK excitations of the L (lepton number) gauge boson can provide a dominant contribution to $(g-2)_\mu$ and explain the $\Delta a_\mu^{\rm ex}$ discrepancy reported by BNL and Fermilab. In the case of two extra dimensions, the summation of KK modes gives an additional factor of $\mathcal{O}(10)$ change in the prediction for Δa_μ compared to that of a single Z'-gauge boson, and this is pivotal to avoid the violation of lepton flavor universality in accommodating the data. The KK tower, which will be within reach of the future muon smasher [27], may become the smoking gun of low-scale gravity models and large extra dimensions.

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.

Acknowledgements

The work of L.A.A. is supported by the U.S. National Science Foundation (NSF Grant PHY-2112527). The research of I.A. was partially performed as International professor of the Francqui Foundation, Belgium. The work of X.H. is supported by the NSFC Grant No. 12047502. The work of D.L. is supported by the Origins Excellence Cluster. The work of T.R.T. is supported by NSF under Grant Number PHY-1913328. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the NSF.

References

[1] N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, The hierarchy problem and new dimensions at a millimeter, Phys. Lett. B 429 (1998) 263–272, https://doi.org/10.1016/S0370-2693(98)00466-3, arXiv:hep-ph/9803315 [hep-ph].

[2] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos, G.R. Dvali, New dimensions at a millimeter to a Fermi and superstrings at a TeV, Phys. Lett. B 436 (1998) 257–263, https://doi.org/10.1016/S0370-2693(98)00860-0, arXiv:hep-ph/9804398 [hep-ph].

[3] I. Antoniadis, E. Kiritsis, T.N. Tomaras, A D-brane alternative to unification, Phys. Lett. B 486 (2000) 186, https://doi.org/10.1016/S0370-2693(00)00733-4, arXiv:hep-ph/0004214.

[4] R. Blumenhagen, L. Goerlich, B. Kors, D. Lüst, Noncommutative compactifications of type I strings on tori with magnetic background flux, J. High Energy Phys. 10 (2000) 006, https://doi.org/10.1088/1126-6708/2000/10/006, arXiv:hep-th/0007024 [hep-th].

[5] I. Antoniadis, E. Kiritsis, J. Rizos, T.N. Tomaras, D-branes and the standard model, Nucl. Phys. B 660 (2003) 81, https://doi.org/10.1016/S0550-3213(03)00256-6, arXiv:hep-th/0210263.

[6] R. Blumenhagen, M. Cvetic, P. Langacker, G. Shiu, Toward realistic intersecting D-brane models, Annu. Rev. Nucl. Part. Sci. 55 (2005) 71, https://doi.org/10.1146/annurev.nucl.55.090704.151541, arXiv:hep-th/0502005.

[7] R. Blumenhagen, B. Kors, D. Lüst, S. Stieberger, Four-dimensional string compactifications with D-branes, orientifolds and fluxes, Phys. Rep. 445 (2007) 1, https://doi.org/10.1016/j.physrep.2007.04.003, arXiv:hep-th/0610327.

[8] A. Sagnotti, A note on the Green-Schwarz mechanism in open string theories, Phys. Lett. B 294 (1992) 196, https://doi.org/10.1016/0370-2693(92)90682-T, arXiv:hep-th/9210127.

[9] L.E. Ibanez, R. Rabadan, A.M. Uranga, Anomalous $U(1)$'s in type I and type IIB $D=4$, $N=1$ string vacua, Nucl. Phys. B 542 (1999) 112, https://doi.org/10.1016/S0550-3213(98)00791-3, arXiv:hep-th/9808139.

[10] E. Poppitz, On the one loop Fayet-Iliopoulos term in chiral four-dimensional type I orbifolds, Nucl. Phys. B 542 (1999) 31, https://doi.org/10.1016/S0550-3213(98)00793-7, arXiv:hep-th/9810010.

[11] L.E. Ibanez, F. Quevedo, Anomalous $U(1)$'s and proton stability in brane models, J. High Energy Phys. 10 (1999) 001, https://doi.org/10.1088/1126-6708/1999/10/001, arXiv:hep-ph/9908305 [hep-ph].

[12] B. Abi, et al., Muon $g-2$ Collaboration, Measurement of the positive muon anomalous magnetic moment to 0.46 ppm, Phys. Rev. Lett. 126 (14) (2021) 141801, https://doi.org/10.1103/PhysRevLett.126.141801, arXiv:2104.03281 [hep-ex].

[13] T. Aoyama, N. Asmussen, M. Benayoun, J. Bijnens, T. Blum, M. Bruno, I. Caprini, C.M. Carloni Calame, M. Cè, G. Colangelo, et al., The anomalous magnetic moment of the muon in the Standard Model, Phys. Rep. 887 (2020) 1–166, https://doi.org/10.1016/j.physrep.2020.07.006, arXiv:2006.04822 [hep-ph].

[14] G.W. Bennett, et al., Muon $g-2$ Collaboration, Final report of the muon E821 anomalous magnetic moment measurement at BNL, Phys. Rev. D 73 (2006) 072003, https://doi.org/10.1103/PhysRevD.73.072003, arXiv:hep-ex/0602035 [hep-ex].

[15] S. Borsanyi, Z. Fodor, J.N. Guenther, C. Hoelbling, S.D. Katz, L. Lellouch, T. Lippert, K. Miura, L. Parato, K.K. Szabo, et al., Leading hadronic contribution to the muon 2 magnetic moment from lattice QCD, https://doi.org/10.1038/s41586-021-03418-1, arXiv:2002.12347 [hep-lat].

[16] M.D. Schwartz, Quantum Field Theory and the Standard Model, Cambridge University Press, 2014, pp. 318–321.

[17] I. Antoniadis, K. Benakli, Limits on extra dimensions in orbifold compactifications of superstrings, Phys. Lett. B 326 (1994) 69–78, https://doi.org/10.1016/0370-2693(94)91194-0, arXiv:hep-th/9310151 [hep-th].

[18] T. Appelquist, B.A. Dobrescu, A.R. Hopper, Nonexotic neutral gauge bosons, Phys. Rev. D 68 (2003) 035012, https://doi.org/10.1103/PhysRevD.68.035012, arXiv:hep-ph/0212073 [hep-ph].

[19] L.A. Anchordoqui, I. Antoniadis, X. Huang, D. Lüst, T.R. Taylor, Muon $g-2$ discrepancy within D-brane string compactifications, Fortschr. Phys. 2100084 (2021), https://doi.org/10.1002/prop.202100084, arXiv:2104.06854 [hep-ph].

[20] L.A. Anchordoqui, I. Antoniadis, H. Goldberg, X. Huang, D. Lüst, T.R. Taylor, Z'-gauge bosons as harbingers of low mass strings, Phys. Rev. D 85 (2012) 086003, https://doi.org/10.1103/PhysRevD.85.086003, arXiv:1107.4309 [hep-ph].

[21] A.M. Sirunyan, et al., CMS Collaboration, Search for high mass dijet resonances with a new background prediction method in proton-proton collisions at $\sqrt{s} = 13$ TeV, J. High Energy Phys. 05 (2020) 033, https://doi.org/10.1007/JHEP05(2020)033, arXiv:1911.03947 [hep-ex].

[22] A.M. Sirunyan, et al., CMS Collaboration, Search for resonant and nonresonant new phenomena in high-mass dilepton final states at $\sqrt{s} = 13$ TeV, arXiv:2103.02708 [hep-ex].

[23] A.J. Buras, A. Crivellin, F. Kirk, C.A. Manzari, M. Montull, Global analysis of leptophilic Z' bosons, J. High Energy Phys. 06 (2021) 068, https://doi.org/10.1007/JHEP06(2021)068, arXiv:2104.07680 [hep-ph].

[24] E. Accomando, A. Belyaev, L. Fedeli, S.F. King, C. Shepherd-Themistocleous, Z' physics with early LHC data, Phys. Rev. D 83 (2011) 075012, https://doi.org/10.1103/PhysRevD.83.075012, arXiv:1010.6058 [hep-ph].

[25] G. Altarelli, B. Mele, M. Ruiz-Altaba, Searching for new heavy vector bosons in $p\bar{p}$ colliders, Z. Phys. C 45 (1989) 109, https://doi.org/10.1007/BF01556677; Erratum: Z. Phys. C 47 (1990) 676.

[26] E. Kiritsis, P. Anastasopoulos, The anomalous magnetic moment of the muon in the D-brane realization of the standard model, J. High Energy Phys. 05 (2002) 054, https://doi.org/10.1088/1126-6708/2002/05/054, arXiv:hep-ph/0201295 [hep-ph].

[27] H. Al Ali, N. Arkani-Hamed, I. Banta, S. Benevedes, D. Buttazzo, T. Cai, J. Cheng, T. Cohen, N. Craig, M. Ekhterachian, et al., The muon smasher's guide, arXiv:2103.14043 [hep-ph].