A New Probe of Cosmic Birefringence Using Galaxy Polarization and Shapes

Weichen Winston Yin,[1,*] Liang Dai,[1] Junwu Huang,[2] Lingyuan Ji,[1] and Simone Ferraro[3,1]

[1] *Department of Physics, 366 Physics North MC 7300, University of California, Berkeley, CA 94720, USA*
[2] *Perimeter Institute for Theoretical Physics, 31 Caroline St. N., Waterloo, Ontario N2L 2Y5, Canada*
[3] *Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

(Dated: February 29, 2024)

We propose a new method to search for parity-violating new physics via measurements of cosmic birefringence and demonstrate its power in detecting the topological effect originating from an axion string network with an axion-photon coupling as a motivated source of cosmic birefringence. The method, using large galaxy samples, exploits an empirical correlation between the polarization direction of the integrated radio emission from a spiral galaxy and its apparent shape. We devise unbiased minimum-variance quadratic estimators for discrete samples of galaxies with both integrated radio polarization and shape measurements. Assuming a synergy with overlapping optical imaging surveys, we forecast the sensitivity to polarization rotation of the forthcoming SKA radio continuum surveys of spiral galaxies out to $z \sim 1.5$. The angular noise power spectrum of polarization rotation using our method can be lower than that expected from CMB Stage-IV experiments, when assuming a wide survey covering $\sim 1000\,\mathrm{deg}^2$ and reaching an RMS flux of $\sim 1\,\mu\mathrm{Jy}$. Our method will be complementary to CMB-based methods as it will be subject to different systematics. It can be generalized to probe time-varying or redshift-varying birefringence signals.

Introduction — The question of whether discrete transformations—charge conjugation (C), parity (P), and time reversal (T)—are fundamental symmetries of the Universe has led to important discoveries [1–3]. The axion was originally proposed to solve the strong CP problem in Quantum Chromodynamics [4–7]. More recently, generic axions are shown to arise abundantly in string theory [8, 9]. The Chern-Simons interaction between the axion and electromagnetism leads to the parity-violating cosmic birefringence effect [10]:

$$\mathcal{L} = -\frac{1}{4}\, g_{a\gamma\gamma}\, a\, F^{\mu\nu}\, \tilde{F}_{\mu\nu} = g_{a\gamma\gamma}\, a\, \mathbf{E}\cdot\mathbf{B}, \tag{1}$$

where a is the axion field, $F^{\mu\nu}$ is the electromagnetic field strength tensor, and $\tilde{F}^{\mu\nu} \equiv (1/2)\, \epsilon_{\mu\nu\rho\sigma}\, F^{\rho\sigma}$ is its dual. As a photon travels through a background axion field, its plane of polarization rotates by an angle proportional to the net change in the axion field value along the photon's worldline, multiplied by the axion-photon coupling constant $g_{a\gamma\gamma}$. The rotation is independent of the photon's frequency due to the topological nature of the interaction [11–13]. Recent analyses of the cosmic microwave background (CMB) have shown hints of a rotation of its polarization anisotropies that is highly coherent across the sky, on the order of a fraction of a degree [14, 15]. Possible contamination from foregrounds is being investigated [16]. On the other hand, searches for anisotropic birefrigence have not so far uncovered a signal [17–20].

Measuring birefringence toward any single astrophysical source or along any single sightline is hindered by our lack of knowledge about the *intrinsic* polarization direction of the source. When the CMB is used as the probe, this fundamental problem is solved statistically. Rotation angles that are correlated across the sky are measurable owing to the state-of-the-art cosmological model that accurately predicts the Gaussian statistics of the primary CMB polarization anisotropies [20–23]. To confidently confirm a signal of cosmic birefringence, it is important to consider alternative methods of detection based on distinct cosmological or astrophysical probes whose systematics are independent of CMB measurements.

In this paper, we propose a new probe of cosmic birefringence that relies on a large sample of spiral galaxies with both radio polarization and apparent shape measurements. This is motivated by empirical findings that the *integrated* radio emission of nearby spiral galaxies, at least at 4.8 GHz, is significantly polarized and aligns on average with the apparent minor axis of the optical galactic disk [24]. A plausible explanation for this alignment is that the polarized radio emission is predominantly synchrotron radiation powered by star-formation feedback and has a polarization direction perpendicular to the local toroidal magnetic field that is ordered on the galactic scale. Integrating over the entire disk results in a nonzero net polarization if the disk is inclined. It seems reasonable to assume that a similar empirical correlation is true for a cosmological population of spiral galaxies. The apparent disk shape can be measured with either optical imaging or interferometric radio imaging, with the former available from existing weak lensing catalogs [25–27] or from upcoming imaging surveys [28, 29].

In reality, the polarization-shape alignment is imperfect either due to the poloidal component of the ordered magnetic field or due to randomly arising asymmetry in the disk structure. Nonetheless, one expects that the mean polarization-shape misalignment angle is zero among a sample of unrelated galaxies, as long as all the physics on the (sub-)galactic scale responsible for the

* winstonyin@berkeley.edu

Prepared for submission to JHEP

Three-leg form factor on Coulomb branch

A.V. Belitsky,[a] **L.V. Bork,**[b] **J.M. Grumski-Flores,**[a] **V.A. Smirnov**[c]

[a] *Department of Physics, Arizona State University, Tempe, AZ 85287-1504, USA*

[b] *Institute for Theoretical and Experimental Physics, 117218 Moscow, Russia*
The Center for Fundamental and Applied Research, 127030 Moscow, Russia

[c] *Skobeltsyn Institute of Nuclear Physics, Moscow State University 119992 Moscow, Russia*
Moscow Center for Fundamental and Applied Mathematics 119992 Moscow, Russia

Abstract: We study the form factor of the lowest component of the stress-tensor multiplet away from the origin of the moduli space in the spontaneously broken, aka Coulomb, phase of the maximally supersymmetric Yang-Mills theory for decay into three massive W-bosons. The calculations are done at two-loop order by deriving and solving canonical differential equations in the asymptotical limit of nearly vanishing W-masses. We confirm our previous findings that infrared physics of 'off-shell observables' is governed by the octagon anomalous dimension rather than the cusp. In addition, the form factor in question possesses a nontrivial remainder function, which was found to be identical to the massless case, upon a proper subtraction of infrared logarithms (and finite terms). However, the iterative structure of the object is more intricate and is not simply related to the previous orders in coupling as opposed to amplitudes/form factors at the origin of the moduli space.

Real-time scattering in the lattice Schwinger model

Irene Papaefstathiou,[1,2] Johannes Knolle,[3,2,4] and Mari Carmen Bañuls[1,2]

[1] *Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Str. 1, D-85748 Garching, Germany*
[2] *Munich Center for Quantum Science and Technology (MCQST), 80799 Munich, Germany*
[3] *Department of Physics TQM, Technische Universität München, James-Franck-Straße 1, D-85748 Garching, Germany*
[4] *Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom*

(Dated: February 29, 2024)

Tensor network methods have demonstrated their suitability for the study of equilibrium properties of lattice gauge theories, even close to the continuum limit. We use them in an out-of-equilibrium scenario, much less explored so far, by simulating the real-time collisions of composite mesons in the lattice Schwinger model. Constructing wave-packets of vector mesons at different incoming momenta, we observe the opening of the inelastic channel in which two heavier mesons are produced and identify the momentum threshold. To detect the products of the collision in the strong coupling regime we propose local quantitites that could be measured in current quantum simulation platforms.

I. INTRODUCTION

Scattering experiments are a well-established tool for probing fundamental physics. In particular, collision experiments allow the production of high energy and rare particles and thereby a study of their interactions. Precise theoretical predictions of such processes, necessary for their interpretation, often involve contributions that can not be extracted from diagrammatic perturbation theory. This is the case, for instance, for hadron collisions, where non-perturbative effects of Quantum Chromodynamics (QCD) may play a significant role [1]. The most powerful tool to address such non-perturbative regimes is lattice gauge theory (LGT), the discrete formulation of gauge field theories [2]. Using advanced numerical methods, like Quantum Monte Carlo [3, 4], LGT has allowed the successful exploration of strong coupling phenomena, such as the hadron spectra in QCD, but real time dynamics represents a challenge. Despite recent progress [5], a precise first-principles calculation of the scattering processes has not yet been possible, one of the reasons that motivates the search for alternative techniques [6].

In recent years quantum methods have unveiled potential alternative ways to explore fundamental physics (see [7–11] for reviews). Their central focus are LGTs, which also appear as effective low-energy descriptions of strongly correlated condensed matter systems [12]. The Hamiltonian version of LGTs then constitutes a natural object for quantum simulations. While a full simulation of QCD is still beyond reach, current efforts are focused on simplified and low-dimensional LGTs. An important development are the quantum-information based tensor network (TN) methods [13–18] which have been successfully applied to study spectral and thermal equilibrium properties of low dimensional LGTs [6, 19–23], in 1+1D cases achieving some of the most precise existing extrapolations to the continuum.

Real time evolution phenomena, such as scattering dynamics, are among the most promising problems for a potential quantum advantage [24], since Monte Carlo methods suffer in this case from a sign problem. Tensor network algorithms, on the other hand, can be used to simulate LGT dynamics, but only for a limited time, before the entanglement in the system becomes too large for an efficient TN description. Yet, out-of-equilibrium simulations of LGT with TN have been used to explore the dynamics of pair production [25] and string breaking dynamics in several LGT models [26–30]. Whereas far from the precision achieved by their equilibrium counterparts and not extrapolated to the continuum limit, such simulations overcome the limits of classical Monte Carlo methods and constitute a valuable tool to prepare and analyze the potential quantum simulations.

More recently, scattering experiments in LGT have attracted the attention of TN calculations and quantum simulation proposals [28, 31, 32]. The basic phenomenology of confinement [33, 34] and meson scattering has also been explored recently in quantum spin models which share properties of LGT especially in 1+1D [35–40].

In this paper we use TN techniques to study elastic and inelastic scattering of composite particles in the lattice Schwinger model, which is the discrete lattice version of Quantum Electrodynamics in one spatial dimension. Due to its similarities with more complex LGTs, including confinement and chiral symmetry breaking, the Schwinger model is a standard testbench for LGT methods, and has been focus of TN simulations, quantum simulation proposals and even experimental realizations (see [7, 41] for reviews). Studies of scattering processes in the Schwinger model have been more scarce.

In absence of a background field, the spectrum of the model contains two stable particles, referred to as *vector* and *scalar*. Elastic processes between two vector mesons, below the threshold of production of the scalar, have been simulated in the strong coupling [28] and in the weak and intermediate coupling [31] regimes. In this regime, the particles collide and can bounce back, without the creation of new particles post-collision, but generating entanglement between the mesons. A first approach to the inelastic regime was explored recently in [32], with a focus on the thermodynamic limit and the non-perturbative regime near the confinement-deconfinement critical point, and using a bosonized formulation of the model, aimed at proposing a quantum simulation scheme that could be

Infrared fixed point in the massless twelve-flavor SU(3) gauge-fermion system

Anna Hasenfratz[1, *] and Curtis T. Peterson[1, †]

[1] Department of Physics, University of Colorado, Boulder, Colorado 80309, USA

We present strong numerical evidence for the existence of an infrared fixed point in the renormalization group flow of the SU(3) gauge-fermion system with twelve massless fermions in the fundamental representation. Our numerical simulations using nHYP-smeared staggered fermions with Pauli-Villars improvement do not exhibit any first-order bulk phase transition in the investigated parameter region. We utilize an infinite volume renormalization scheme based on the gradient flow transformation to determine the renormalization group β function. We identify an infrared fixed point at $g^2_{\mathrm{GF}\star} = 6.69(68)$ in the GF scheme and calculate the leading irrelevant critical exponent $\gamma_g^\star = 0.204(36)$. Our prediction for $\gamma_g^\star$ is consistent with available literature at the 1-2σ level.

I. INTRODUCTION

The infrared properties of the SU(3) gauge-fermion system with $N_f = 12$ massless fundamental flavors has been studied extensively using a variety of analytical and numerical techniques. Such techniques include perturbation theory [1–5], use of the gap equation [6, 7], functional renormalization group methods [8, 9], conformal expansion [10], conformal bootstrap [11], the background field method [12], perturbative non-relativistic quantum chromodynamics [13], large-N expansion [14], and nonperturbative lattice simulations [15–38]. Investigations based on lattice simulations have utilized finite-volume step-scaling [15–24], Monte Carlo renormalization group methods [25, 26], hadron mass and decay constant spectroscopy [28–36], and the Dirac eigenmode spectrum [37, 38]. Many investigations suggest that the $N_f = 12$ system is infrared conformal[1], though a minority of studies conclude that the system is confining with chiral symmetry breaking, or are inconclusive, as they find neither direct evidence of chiral symmetry breaking nor of an infrared fixed point[2].

Most lattice studies are affected by the presence of a bulk first-order phase transition [40–45]. Such unphysical phase transitions are triggered by strong ultraviolet fluctuations in the fermion sector that prevent lattice simulations from reaching deep into the infrared regime. Even when strong couplings are reached, lattice cutoff effects make it difficult to take the proper continuum limit, leading to inconsistent results between different lattice formulations. It is imperative to reduce the ultraviolet fluctuations that trigger first-order bulk phase transitions. Ref. [46] suggested to include unphysical heavy Pauli-Villars fields to achieve the necessary improvement. Lattice Pauli-Villars fields are similar to their continuum analogue - they have the same action as the fermions, but possess bosonic statistics. Their mass is at the level of the cutoff. Therefore, they decouple in the infrared limit,

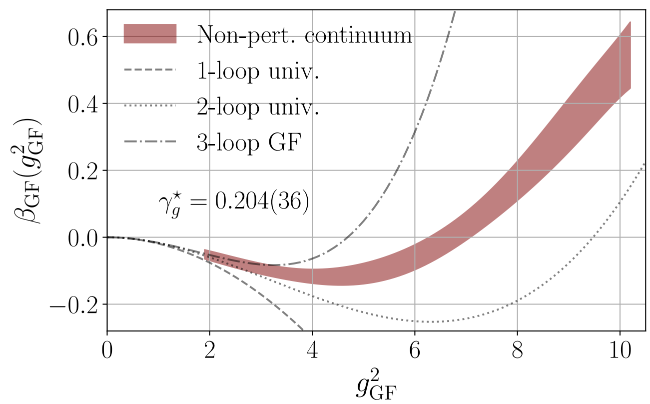

FIG. 1. Our continuum prediction for $\beta_{\mathrm{GF}}(g^2_{\mathrm{GF}})$ as a function of g^2_{GF} (maroon band) juxtaposed against the 1- (dashed), 2- (dotted) and 3-loop (dashed-dotted) gradient flow β function from perturbation theory [49]. The width of the maroon band indicates the error. Also given is our prediction for the leading irrelevant critical exponent at the IRFP, $\gamma_g^\star = 0.204(36)$.

while in the ultraviolet they compensate for cutoff effects introduced by the fermions. This idea has been tested in simulations of the SU(3) gauge-fermion system with ten massless fundamental Dirac fermions (flavors) and the SU(4) gauge-fermion system four massless fundamental and four massless two-index Dirac fermions [47, 48]. Both studies extended the reach into the infrared regime significantly, and both present clear evidence for infrared conformality in those systems. See also Refs. [43, 44] for an alternative proposal to remove unphysical bulk phase transitions.

In this work, we utilize Pauli-Villars (PV) improvement to study the infrared properties of the massless SU(3) gauge-fermion system with $N_f = 12$ fundamental flavors. We calculate the renormalization group (RG) β function, defined as the logarithmic derivative of the renormalized running coupling $g^2(\mu)$ with respect to an energy scale μ as

$$\beta(g^2) = \mu^2 \frac{\mathrm{d}g^2(\mu)}{\mathrm{d}\mu^2}. \tag{1}$$

If the β function exhibits a fixed point at some coupling

* anna.hasenfratz@colorado.edu
† curtis.peterson@colorado.edu

[1] See Refs. [1–3, 5–7, 10, 11, 15–17, 20, 23–26, 28, 30, 31, 33–36, 38]
[2] See Refs. [12, 14, 18, 19, 29, 32, 39]

Casimir Physics beyond the Proximity Force Approximation: The Derivative Expansion

César D. Fosco,[1] Fernando C. Lombardo,[2,3] and Fransisc D. Mazzitelli[1]

[1] *Centro Atómico Bariloche, Instituto Balseiro, Comisión Nacional de Energía Atómica, 8400 Bariloche, Argentina*

[2] *Departamento de Física, Facultad de Ciencias Exactas y Naturales, Universidad de Buenos Aires, Buenos Aires, Argentina*

[3] *Instituto de Física de Buenos Aires (IFIBA), CONICET, Universidad de Buenos Aires, Argentina*

We review the derivative expansion (DE) method in Casimir physics, an approach which extends the proximity force approximation (PFA). After introducing and motivating the DE in contexts other than the Casimir effect, we present different examples which correspond to that realm. We focus on different particular geometries, boundary conditions, types of fields, and quantum and thermal fluctuations. Besides providing various examples where the method can be applied, we discuss a concrete example for which the DE cannot be applied; namely, the case of perfect Neumann conditions in 2 + 1 dimensions. By the same example, we show how a more realistic type of boundary condition circumvents the problem. We also comment on the application of the DE to the Casimir–Polder interaction which provides a broader perspective on particle–surface interactions.

arXiv:2402.17864v1 [quant-ph] 27 Feb 2024

I. INTRODUCTION

Casimir forces are one of the most intriguing macroscopic manifestations of quantum fluctuations in Nature. Their existence, first realized in the specific context of the interaction between the quantum electromagnetic (EM) field and the boundaries of two neutral bodies, manifests itself as an attractive force between them. That force depends, in an intricate manner, on the shape and EM properties of the objects. Since the discovery of this effect by Hendrik Casimir 75 years ago [1] this, and closely related phenomena, have been subjected to intense theoretical and experimental research [2–5]. The outcome of that work has not just revealed fundamental aspects of quantum field theory, but also subtle aspects of the models used to describe the EM properties of material bodies. Besides, it has become increasingly clear that this research has potential applications to nanotechnology.

Theoretical and experimental reasons have called for the calculation of the Casimir energies and forces for different geometries and materials [6], and with an ever increasing accuracy. The simplicity of the theoretical predictions when two parallel plates are involved, corresponds to a difficult experimental setup, due to alignment problems (in spite of this, the Casimir force for this geometry has been measured at the 10% accuracy level [7]). Equivalently, geometries which are more convenient from the experimental point of view, and allow for higher precision measurements, lead to more involved theoretical calculations. Such is the case of a cylinder facing a plane [8], or a sphere facing a plate, which is free from the alluded alignment problems [9–15].

From a theoretical standpoint, finding the dependence of the Casimir energies and forces on the geometry of the objects, poses an interesting challenge. Indeed, even when evaluating the self-energies which result from the coupling on an object to the vacuum field fluctuations, results may be rather non-intuitive; as in the case of a single spherical surface [16].

For a long time, calculations attempting to find analytical results for the Casimir and related interactions had been restricted to using the so called proximity force approximation (PFA). In this approach, the interaction energies and the resulting forces are computed approximating the geometry by a collection of parallel plates and then adding up the contributions obtained for this approximate geometry. This procedure was presumed to work well enough, at least for smooth surfaces when they are sufficiently close to each other; in more precise terms: when the curvature radii of the surfaces R_i are much larger than the distance d between them. Indeed, this is the main content of the Derjaguin approximation (DA), developed by Boris Derjaguin in the 1930s [17–19] , which is pivotal in the study of surface interactions, especially in the context of colloidal particles and biological cells. This approach has significant implications in understanding colloidal stability, adhesion, and thin film formation.

It is worth introducing some essentials of the DA, in particular, of the geometrical aspects involved. Assuming the interaction energy per unit area between two parallel planes at a distance h is known, and given by $E_{\shortparallel}(h)$, the DA yields an expression for the interaction energy between two curved surfaces, $U_{\rm DA}$ [2, 4, 17–20]. Indeed,

$$U_{\rm DA}(a) = 2\pi R_{\rm eff} \int_a^\infty E_{\shortparallel}(h) dh \,, \tag{1}$$

where a denotes the distance between the surfaces, R_1 and R_2 are their curvature radii (at the point of closest distance), while $R_{\rm eff} = R_1 R_2/(R_1 + R_2)$. It is rather straightforward to implement the approximation at the level of the force $f_{\rm DA}$ between surfaces:

$$f_{\rm DA}(a) = 2\pi R_{\rm eff} E_{\shortparallel}(a) \,. \tag{2}$$

This approximation is usually derived from a quite reasonable assumption, namely, that the interaction energy

Breakdown of Hawking Evaporation opens new Mass Window for Primordial Black Holes as Dark Matter Candidate

Valentin Thoss,[1,2,3]⋆ Andreas Burkert[1,2,3] and Kazunori Kohri[4,5,6]
[1] *Universitäts-Sternwarte, Ludwig-Maximilians-Universität München, Scheinerstr. 1, 81679 Munich, Germany*
[2] *Max-Planck Institute for Extraterrestrial Physics, Giessenbachstr. 1, 85748 Garching, Germany*
[3] *Excellence Cluster ORIGINS, Boltzmannstrasse 2, 85748 Garching, Germany*
[4] *Division of Science, National Astronomical Observatory of Japan (NAOJ), and SOKENDAI, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*
[5] *Theory Center, IPNS, and QUP, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan*
[6] *Kavli IPMU (WPI), University of Tokyo, Kashiwa, Chiba 277-8568, Japan*

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

The energy injection through Hawking evaporation has been used to put strong constraints on primordial black holes as a dark matter candidate at masses below 10^{17} g. However, Hawking's semiclassical approximation breaks down at latest after half-decay. Beyond this point, the evaporation could be significantly suppressed as was shown in recent work. In this study, we review existing cosmological and astrophysical bounds on primordial black holes taking this effect into account. We show that the constraints disappear completely for a reasonable range of parameters, which opens a new window below 10^{10} g for light primordial black holes as a dark matter candidate.

Key words: dark matter – black hole physics – gamma-rays: general

1 INTRODUCTION

The hypothesis of black holes forming in the early universe has been discussed for more than 50 years (Zel'dovich & Novikov 1967; Hawking 1971; Carr & Hawking 1974), with Chapline (1975) first to suggest that primordial black holes (PBHs) could constitute the entire dark matter of the universe. Since the 1970s, people have studied the consequences of PBHs as a dark matter candidate from the Planck mass $M_{\rm PBH} = M_{\rm pl}$ up to the 'incredulity limit'[1] beyond $M_{\rm PBH} \sim 10^{10}\, M_\odot$. This has led to strong bounds which exclude PBHs of a single mass from constituting the entirety of the dark matter with the exception of a mass window in the asteroid range $M_{\rm PBH} \in [10^{17}, 10^{22}]$ g (Carr et al. 2021, and references therein).

The lower limit is a result of constraints due to black hole evaporation at low masses. This process was first described by Hawking (1974) as he was studying the consequences of light PBHs. He showed that a black hole will emit a thermal spectrum of particles, with the temperature of the radiation scaling as $T \sim 1/M_{\rm PBH}$. The described evaporation process is self-similar and ends with a final burst as $M \to 0$.

It was soon realized that the energy injection from low-mass PBHs is in conflict with observations of γ rays, the cosmic microwave background (CMB) and the abundance of light elements produced during big bang nucleosynthesis (BBN) unless these black holes constitute only a tiny fraction of the dark matter (Chapline 1975; Hawking 1975; Novikov et al. 1979; Carr et al. 2010, for a historical overview). Furthermore, if the PBHs have a mass below $M \simeq 5 \times 10^{14}$ g, they would have completely evaporated by now (see Auffinger (2023) for a review on constraints of evaporating PBHs).

However, it is possible to avoid some of the constraints that are a result of black hole evaporation. Pacheco et al. (2023) have studied 'quasi-extremal' PBHs and found that they can be a viable dark matter candidate. Friedlander et al. (2022) and Anchordoqui et al. (2022) have investigated PBHs in the context of large extra dimensions (Arkani-Hamed et al. 1998) and showed that this opens up new mass windows for light PBHs as dark matter candidate.

In this work, we focus on 'ordinary' 4D black holes. Dvali et al. (2020) have shown that Hawking's semiclassical calculations break down at latest when the black hole has lost roughly half of its initial mass. Hawking's result is only exact in the limit $M \to \infty, G \to 0, r_s = \text{const.}$, where G is the gravitational constant and $r_s = 2GM/c^2$ the Schwarzschild radius. It entirely neglects the backreaction of the emission on the black hole itself. However, this effect can no longer be ignored when the energy of the released quanta becomes comparable to that of the black hole. Dvali et al. (2020) summarize this as: 'An old black hole that lost half of its mass is by no means equivalent to a young classical black hole of equal mass.' The crucial insight by Dvali et al. (2020) is that this backreaction leads to a universal effect of so-called 'memory burden', first introduced by Dvali (2018). This can significantly suppress further evaporation.

As Dvali et al. (2020) have discussed, there are two possibilities for the fate of an evaporating black hole beyond half-decay. Either it continues to emit quanta with a strongly suppressed rate due to the memory burden or a new classical instability sets in. In the latter case, light PBHs cannot constitute the dark matter. However, if the

⋆ E-mail: vthoss@usm.lmu.de

[1] This term was coined by B. Carr and refers to the limit that at least one black hole must exist in a given environment (e.g. galaxy, universe).

Gradient Properties of Perturbative Multiscalar RG Flows to Six Loops

William H. Pannell* and Andreas Stergiou†
Department of Mathematics, King's College London, Strand, London WC2R 2LS, United Kingdom
(Dated: February 2024)

The gradient property of the renormalisation group (RG) flow of multiscalar theories is examined perturbatively in $d = 4$ and $d = 4 - \varepsilon$ dimensions. Such theories undergo RG flows in the space of quartic couplings λ^I. Starting at five loops, the relevant vector field that determines the physical RG flow is not the beta function traditionally computed in a minimal subtraction scheme in dimensional regularisation, but a suitable modification of it, the B function. It is found that up to five loops the B vector field is gradient, i.e. $B^I = G^{IJ}\partial A/\partial\lambda^J$ with A a scalar and G_{IJ} a rank-two symmetric tensor of the couplings. Up to five loops the beta function is also gradient, but it fails to be so at six loops. The conditions under which the B function (and hence the RG flow) is gradient at six loops are specified, but their verification rests on a separate six-loop computation that remains to be performed.

arXiv:2402.17817v1 [hep-th] 27 Feb 2024

Introduction.—Dynamical systems, governed by differential equations of the form

$$\frac{d\vec{x}}{dt} = \vec{F}(\vec{x})\,, \tag{1}$$

appear in every corner of the natural world and are studied in depth in many branches of science and engineering. While general equations like (1) are often intractable with analytic methods, in some favourable cases features of such systems can be drawn out of the equations themselves, without having to resort to finding explicit solutions. One such case is that of gradient systems, where the function $\vec{F}(\vec{x})$ may be written in the form

$$\vec{F}(\vec{x}) = \vec{\nabla} f(\vec{x})\,. \tag{2}$$

Systems undergoing gradient flow have remarkable properties, and it is known from a theorem by Łojasiewicz [1] that at late times all solutions must flow to either a fixed point, where $\vec{F}(\vec{x})$ vanishes, or off to infinity.

In quantum field theory (QFT), the flow of field theories under a change of energy scale, governed by what is called the renormalisation group (RG), is one such dynamical system. As recognised by Wilson [2], the qualitative behaviour of such flows is of immense consequence to the physical system being modelled. In particular, a potential gradient property for the RG flow would have remarkable consequences, e.g. it would preclude periodic flow lines and severely limit the nature of potential endpoints of the RG flow.

In this Letter we will be concerned with the gradient property of RG flow in multiscalar QFTs with N real scalar fields in $d = 4$ and $d = 4 - \varepsilon$ dimensions. These QFTs are defined by the Lagrangian

$$\mathscr{L} = \tfrac{1}{2}\partial^\mu\phi_i\partial_\mu\phi_i + \tfrac{1}{4!}\lambda_{ijkl}\phi_i\phi_j\phi_k\phi_l\,, \tag{3}$$

where indices from the Latin alphabet take values from 1 to N [3]. Such theories are renormalisable in perturbation theory. This requires the bare symmetric tensor λ_{ijkl} to be substituted with a renormalised one, which we will also call λ_{ijkl}, which depends on the renormalisation scale μ:

$$\mu\frac{d\lambda_{ijkl}}{d\mu} = \beta_{ijkl}\,. \tag{4}$$

The quantity β_{ijkl}, called the beta function, is a function of λ and can be computed order by order in a weak-coupling expansion. Its first quantum contribution is of order λ^2 and takes the form

$$\beta_{ijkl} \supset \lambda_{ijmn}\lambda_{mnkl} + \lambda_{ikmn}\lambda_{mnjl} + \lambda_{ilmn}\lambda_{mnjk}\,, \tag{5}$$

which follows from the computation of a one-loop Feynman diagram in momentum space and we have rescaled λ to eliminate the factor of $1/16\pi^2$ that one encounters. This result can be extended to higher orders, and recently [4] used results of [5] to compute β_{ijkl} up to six loops, i.e. order λ^7. Due to the indices carried by λ there is a proliferation of contributions to β_{ijkl} at higher orders, with 2, 7, 23, 110, 571 distinct terms contributing at two, three, four, five and six loops, respectively.

One may think of β_{ijkl} as a vector field β^I in the space of couplings, where I denotes the collection of indices $(ijkl)$. A natural question then is if this vector field can be derived as a gradient of a scalar function. In that case the associated flow would be gradient, and the following equation would hold:

$$\beta^I = G^{IJ}\partial_J A\,, \quad \partial_I = \partial/\partial\lambda^I\,, \tag{6}$$

with G^{IJ} is a rank-two tensor and A a scalar. Both G^{IJ} and A are functions of λ. The metric G_{IJ} should be Riemannian, i.e.

(a) symmetric, $G_{IJ} = G_{JI}$, and

(b) positive-definite, $G \succ 0$.

In the present context of multiscalar theories, the validity of eq. (6) with a Riemannian metric was verified up to three loops some time ago in $d = 4$ and $d = 4-\varepsilon$ [6, 7], and this was more recently extended to four loops in $d = 4$ [8].

Reference frame dependence of the periodically oscillating Coulomb field in the Proca theory

Bogdan Damski
Jagiellonian University, Faculty of Physics, Astronomy and Applied Computer Science, Łojasiewicza 11, 30-348 Kraków, Poland

The Proca theory of the real massive vector field admits non-equilibrium solutions, where the asymptotic dynamics of the electric field is dominated by the periodically oscillating Coulomb component. We discuss how such field configurations are seen in different reference frames, where we find an intriguing spatial pattern of the vector field and the electromagnetic field associated with it. Our studies are carried out in the framework of the classical Proca theory.

I. INTRODUCTION

We consider the simplest version of the Proca theory, which is defined by the following Lagrangian density

$$\mathcal{L} = -\frac{1}{4}(\partial_\mu V_\nu - \partial_\nu V_\mu)^2 + \frac{m^2}{2}(V_\mu)^2, \tag{1}$$

where V is the vector field and $m > 0$ is the mass of the vector boson (see Appendix A for our conventions). This theory is often used to illustrate various field theoretic issues and it describes some properties of massive vector bosons such as ρ and ω mesons [1–3]. Moreover, the Proca theory is considered as an extension of Maxwell electrodynamics [4–6], the one taking into account the possibility that the photon might be a massive particle.

We recently studied the quantum version of the Proca theory in [7], where the periodically oscillating Coulomb field was introduced for the first time. In this work, we focus entirely on the classical version of the Proca theory, where the reference frame dependence of such an unusual field can be most transparently discussed.

To proceed, we introduce the primed reference frame, where the vector field is denoted as V' and the spacetime coordinates are $(t', \boldsymbol{r}')$, where $\boldsymbol{r}' = (x', y', z')$. Then, we consider the following field configuration

$$V'^0(t', \boldsymbol{r}') = -\frac{q}{m^2}\int \frac{d^3k}{(2\pi)^3} f(\omega_k)\exp(\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}')\cos(\varepsilon_k t'), \tag{2a}$$

$$\boldsymbol{V}'(t', \boldsymbol{r}') = \frac{\mathrm{i}q}{m^2}\int \frac{d^3k}{(2\pi)^3} f(\omega_k)\frac{\varepsilon_k}{\omega_k^2}\boldsymbol{k}\exp(\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}')\sin(\varepsilon_k t'), \tag{2b}$$

where q is a constant non-zero parameter, $\omega_k = |\boldsymbol{k}|$, $\varepsilon_k = \sqrt{m^2 + \omega_k^2}$, and real-valued $f(\omega_k)$ weights the Fourier modes in the studied field configuration ($f(0) \neq 0$ is assumed because low frequency modes are of interest in this work). We assume that V' represents the finite-energy field configuration and that its first and second order derivatives over space-time coordinates can be obtained by taking such derivatives under the integral symbol, which facilitates the computation of the electromagnetic field and the verification of Proca field equations. These properties can be ensured by various functions $f(\omega_k)$, e.g. such as those given by (9).

Taking into account the above remarks, one may easily verify that (2) satisfies the Proca field equations in the primed reference frame

$$\Box' V' = -m^2 V', \;\; \partial' \cdot V' = 0, \tag{3}$$

where $\Box' = \partial' \cdot \partial' = \partial^2_{t'} - \partial^2_{x'} - \partial^2_{y'} - \partial^2_{z'}$. Moreover, via $\boldsymbol{E}' = -\partial_{t'}\boldsymbol{V}' - \boldsymbol{\nabla}' V'^0$ and $\boldsymbol{B}' = \boldsymbol{\nabla}' \times \boldsymbol{V}'$, where $\boldsymbol{\nabla}' = (\partial_{x'}, \partial_{y'}, \partial_{z'})$, one may also verify the following expressions for the electromagnetic field

$$\boldsymbol{E}'(t', \boldsymbol{r}') = -\mathrm{i}q\int \frac{d^3k}{(2\pi)^3} f(\omega_k)\frac{\boldsymbol{k}}{\omega_k^2}\exp(\mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}')\cos(\varepsilon_k t'), \tag{4}$$

$$\boldsymbol{B}'(t', \boldsymbol{r}') = \boldsymbol{0}. \tag{5}$$

The discussed field configuration is described by spherically symmetric $V'^0(t', \boldsymbol{r}')$ as well as $\boldsymbol{V}'(t', \boldsymbol{r}') \propto \boldsymbol{r}'$ and $\boldsymbol{E}'(t', \boldsymbol{r}') \propto \boldsymbol{r}'$, where the proportionality factors are a function of t' and $r' = |\boldsymbol{r}'|$ [8]. Thereby, our field configuration is centered around $\boldsymbol{r}' = \boldsymbol{0}$ for all times and as such it is at rest in the primed reference frame. As we deal here with the non-equilibrium solution of (3), the term "at rest" refers to the fact that the analyzed field configuration does not move as a whole in any particular direction. In addition to that, we note that the energy of the studied field configuration is given by

$$\frac{q^2}{4\pi^2 m^2}\int_0^\infty d\omega_k f^2(\omega_k)\varepsilon_k^2. \tag{6}$$

This result has been obtained from the standard expression [1]

$$\frac{1}{2}\int d^3r' \left(|\boldsymbol{E}'(t', \boldsymbol{r}')|^2 + |\boldsymbol{B}'(t', \boldsymbol{r}')|^2 + m^2|\boldsymbol{V}'(t', \boldsymbol{r}')|^2 + m^2[V'^0(t', \boldsymbol{r}')]^2\right), \tag{7}$$

where the presence of the vector field does not cause any problems because such a quantity is observable in the Proca theory (e.g. [9] reports an attempt of the experimental measurement of the vector field of the Proca theory; see the discussion by the end of this section).

Our interest in (2) comes from the fact that the following quantity exhibits intriguing dynamics

$$Q'(t', \mathbb{R}^3) = \int d^3r' \boldsymbol{\nabla}' \cdot \boldsymbol{E}'(t', \boldsymbol{r}') = q\cos(mt'), \tag{8}$$

Dark matter from mediator decay in early matter domination

Rouzbeh Allahverdi *[1], Ngo Phuc Duc Loc †[1], and Jacek K. Osiński ‡[2]

[1]Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM 87131, USA

[2]AstroCeNT, Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences, ul. Rektorska 4, 00-614 Warsaw, Poland

Abstract

We study dark matter production from mediator decays in scenarios with an epoch of early matter domination. Particles that mediate interactions between dark matter and the standard model particles are kinematically accessible to the thermal bath as long as their mass is below the reheating temperature of the Universe after inflation. Decay of on-shell mediators can then lead to copious production of dark matter during early matter domination or a preceding radiation-dominated phase. In particular, for mediators that are charged under the standard model, it can exceed the standard freeze-in channel due to inverse annihilations at much lower temperatures (often by many orders of magnitude). The requirement to obtain the correct relic abundance severely constrains the parameter space for dark matter masses above a few TeV.

1 Introduction

While there are many lines of evidence for the existence of dark matter (DM) in the Universe [1], the identity of DM is an outstanding problem at the interface of particle physics and cosmology. Explaining the observed DM abundance is another challenge that in addition depends on the details of the thermal history of the early Universe. Thermal freeze-out in a radiation-dominated (RD) Universe is a simple and attractive mechanism that can yield the correct relic abundance if the (thermally averaged) DM annihilation rate takes the specific value $\langle \sigma_{\rm ann} v \rangle = 3 \times 10^{-26} {\rm cm}^3 \ {\rm s}^{-1}$. However, in nonstandard cosmological histories, the correct DM abundance can be obtained for much larger or smaller values of $\langle \sigma_{\rm ann} v \rangle$ [2, 3].

It is known that well-motivated classes of models arising from string theory generically lead to nonstandard histories that involve one or more epochs of early matter domination (EMD) [4]. In general, an EMD phase arises when a matter-like component dominates the energy density of the Universe and eventually decays to establish a RD Universe prior to big bang nucleosynthesis (BBN). The matter equation of state can be due to coherent oscillations

*rouzbeh@unm.edu
†locngo148@gmail.com
‡jaksaosinski@gmail.com

Minimal seesaw and leptogenesis with the smallest modular finite group

Simone Marciano,[†] Davide Meloni,[‡] Matteo Parriciatu,[§]

Dipartimento di Matematica e Fisica, Università di Roma Tre
INFN Sezione di Roma Tre, Via della Vasca Navale 84, 00146, Roma, Italy

Abstract

We propose a model for leptons based on the smallest modular finite group $\Gamma_2 \cong S_3$ that, for the first time, accounts for both the hints of large low-energy CP-violation in the lepton sector and the matter-antimatter asymmetry of the Universe, generated by only two heavy right-handed neutrinos. These same states are also employed in a Minimal seesaw mechanism to generate light neutrino masses. Besides the heavy neutrinos, our particle content is the same as the Standard Model (SM), with the addition of one single modulus τ, whose vacuum expectation value is responsible for both the modular and CP-symmetry breakings. We show that this minimalistic SM extension is enough to get an excellent fit to low energy neutrino observables and to the required baryon asymmetry η_B. Predictions for the neutrino mass ordering, effective masses in neutrinoless double beta decay and tritium decay as well as for the Majorana phases are also provided.

Contents

[†]e-mail address: simone.marciano@uniroma3.it
[‡]e-mail address: davide.meloni@uniroma3.it
[§]e-mail address: matteo.parriciatu@uniroma3.it

ULB-TH/24-01

Dark matter bound-state formation in the Sun

Xiaoyong Chu,[1,*] Raghuveer Garani,[2,†] Camilo García-Cely,[3,‡] and Thomas Hambye[4,5,§]

[1]*Institute of High Energy Physics, Austrian Academy of Sciences, Nikolsdorfer Gasse 18, 1050 Vienna, Austria*

[2]*INFN Sezione di Firenze, Via G. Sansone 1, I-50019 Sesto Fiorentino, Italy*

[3]*Instituto de Física Corpuscular (IFIC), Universitat de València-CSIC, Parc Científic UV, C/ Catedrático José Beltrán 2, E-46980 Paterna, Spain*

[4]*Service de Physique Théorique Université Libre de Bruxelles, Boulevard du Triomphe, CP225, 1050 Brussels, Belgium*

[5]*CERN, Theoretical Physics Department, Geneva, Switzerland*

The Sun may capture asymmetric dark matter (DM), which can subsequently form bound-states through the radiative emission of a sub-GeV scalar. This process enables generation of scalars without requiring DM annihilation. In addition to DM capture on nucleons, the DM-scalar coupling responsible for bound-state formation also induces capture from self-scatterings of ambient DM particles with DM particles already captured, as well as with DM bound-states formed in-situ within the Sun. This scenario is studied in detail by solving Boltzmann equations numerically and analytically. In particular, we take into consideration that the DM self-capture rates require a treatment beyond the conventional Born approximation. We show that, thanks to DM scatterings on bound-states, the number of DM particles captured increases exponentially, leading to enhanced emission of relativistic scalars through bound-state formation, whose final decay products could be observable. We explore phenomenological signatures with the example that the scalar mediator decays to neutrinos. We find that the neutrino flux emitted can be comparable to atmospheric neutrino fluxes within the range of energies below one hundred MeV. Future facilities like Hyper-K, and direct DM detection experiments can further test such scenario.

* xiaoyong.chu@oeaw.ac.at

† garani@fi.infn.it

‡ camilo.garcia@ific.uv.es

§ thomas.hambye@ulb.be

Polarized and unpolarized off-shell $H^* \to ZZ \to 4\ell$ decay above the $2m_Z$ threshold

A. I. Hernández-Juárez*,[1] R. Gaitán,[1] and G. Tavares-Velasco[2]

[1]*Departamento de Física, FES-Cuautitlán, Universidad Nacional Autónoma de México, C.P. 54770, Estado de México, México.**

[2]*Facultad de Ciencias Físico Matemáticas, Benemérita Universidad Autónoma de Puebla, Apartado Postal 1152, Puebla, Puebla, México*

(Dated: February 29, 2024)

An analysis of the off-shell $H^* \to ZZ \to \bar{\ell}_1\ell_1\bar{\ell}_2\ell_2$ decay width is presented for both unpolarized and polarized Z gauge bosons in the scenario with the most general H^*ZZ vertex function, which is given in terms of two CP-even ($\hat{b}_Z$ and $\hat{c}_Z$) and one CP-odd ($\tilde{b}_Z$) anomalous couplings. The SM contributions to the H^*ZZ coupling up to the one-loop level are also included. Explicit analytic results for the unpolarized and polarized $H^* \to ZZ \to \bar{\ell}_1\ell_1\bar{\ell}_2\ell_2$ square amplitudes and the four-body phase space are presented, out of which several observable quantities can be obtained straightforwardly. As far as the numerical analysis is concerned, a cross-check is performed via Madgraph, where our model was implemented with the aid of FeynRules. We then consider the most stringent bounds on anomalous complex H^*ZZ couplings and analyze the effects of the polarizations of the Z gauge bosons through the polarized $H^* \to ZZ \to \bar{\ell}_1\ell_1\bar{\ell}_2\ell_2$ decay width as well as left-right and forward-backward asymmetries, which are found to be sensitive to new-physics effects. Particular focus is put on the effects of the absorptive parts of the anomalous H^*ZZ couplings, which have been largely overlooked up to now in LHC analyses. It is found that the studied observable quantities, particularly the left-right asymmetries, can be helpful to look for effects of CP-violation in the H^*ZZ coupling and set bounds on the absorptive parts at the LHC and future colliders. For completeness we also analyze the case of unpolarized Z gauge bosons.

arXiv:2402.18497v1 [hep-ph] 28 Feb 2024

I. INTRODUCTION

All the experimental data collected until now indicate that the properties of the scalar particle discovered in 2012 at the LHC by the ATLAS and CMS collaborations [1, 2] are compatible with those of the long-sought-for Higgs boson, which is the remanent of the mechanism of spontaneous symmetry breaking of the $SU(2)_L \times U(1)_Y$ gauge symmetry in the Glashow-Salam-Weinberg Standard Model (SM). Nonetheless, there are still several couplings of such a particle that remain to be measured with enough accuracy, such as for the $H\bar{b}b$ and $H\mu^-\mu^+$ interactions, whereas other ones are still not yet at the reach of experimental measurement, such as the Higgs boson couplings to light fermions, let alone the Higgs boson self couplings. Therefore, the study of the Higgs boson phenomenology is expected to play an important role to probe the SM and search for any new physics effects in present and future colliders. Along these lines, the Higgs boson couplings to the weak gauge bosons HZZ and HWW, which in the SM arise at the tree level, have long drawn considerable attention both theoretically and experimentally. As far as the HZZ coupling is concerned, it has played a crucial part in the experimental study of the Higgs boson at the LHC via the $H \to ZZ^* \to 4\ell$ decay, which provides a clear signal and allows for a precise resolution of the Higgs boson mass despite that its branching ratio is considerably smaller than those of other decay channels such as $H \to WW^*$, $H \to \tau^+\tau^-$, and $H \to \bar{b}b$.

Although one-loop corrections to the HZZ vertex were calculated long ago in the framework of the SM [3, 4], more recently a new evaluation was presented [5] that could be more suitable for the recent progress on the theoretical and experimental study of this coupling. The most general HZZ vertex can be parametrized by an effective Lagrangian given in terms of four coupling constants:

$$\mathcal{L}^{HZZ} = \frac{g}{c_W} m_Z \left[\frac{(1-a_Z)}{2} H Z_\mu Z^\mu + \frac{1}{2m_Z^2} \left\{ \hat{b}_Z H Z_{\mu\nu} Z^{\mu\nu} + \hat{c}_Z H Z_\mu \partial_\nu Z^{\mu\nu} + \widetilde{b}_Z H Z_{\mu\nu} \widetilde{Z}^{\mu\nu} \right\} \right], \tag{1}$$

where a_Z stands for the corrections to the SM tree-level coupling via loop contributions or new physics effects, whereas $\hat{b}_Z$, $\hat{c}_Z$ and $\widetilde{b}_Z$ are absent at the tree level in the SM and thus are dubbed anomalous couplings. While the anomalous CP-conserving coupling $\hat{b}_Z$ is induced at the one-loop level [3, 4] and can reach values of the order of 10^{-3} [5], the CP-violating one $\widetilde{b}_Z$ would arise up to the three-loop level and has been estimated to be of the order of 10^{-11} [6].

---

* alaban7_3@hotmail.com

CPPC-2024-01, MS-TP-24-06

Prepared for submission to JCAP

Towards a precision calculation of $N_{\rm eff}$ in the Standard Model III: Improved estimate of NLO corrections to the collision integral

Marco Drewes,[a] **Yannis Georis,**[a] **Michael Klasen,**[b] **Luca Paolo Wiggering**[b] **and Yvonne Y. Y. Wong**[c]

[a]Centre for Cosmology, Particle Physics and Phenomenology, Université catholique de Louvain, Louvain-la-Neuve B-1348, Belgium

[b]Institut für Theoretische Physik, Universität Münster, Wilhelm-Klemm-Straße 9, D-48149 Münster, Germany

[c]Sydney Consortium for Particle Physics and Cosmology, School of Physics, The University of New South Wales, Sydney NSW 2052, Australia

E-mail: marco.drewes@uclouvain.be, yannis.georis@uclouvain.be, michael.klasen@uni-muenster.de, luca.wiggering@uni-muenster.de, yvonne.y.wong@unsw.edu.au

Abstract. We compute the dominant QED correction to the neutrino-electron interaction rate in the vicinity of neutrino decoupling in the early universe, and estimate its impact on the effective number of neutrino species $N_{\rm eff}$ in cosmic microwave background anisotropy observations. We find that the correction to the interaction rate is at the sub-percent level, consistent with a recent estimate by Jackson and Laine. Relative to that work we include the electron mass in our computations, but restrict our analysis to the enhanced t-channel contributions. The fractional change in $N_{\rm eff}^{\rm SM}$ due to the rate correction is of order 10^{-5} or below, i.e., about a factor of 30 smaller than that recently claimed by Cielo *et al.*, and below the nominal computational uncertainties of the current benchmark value of $N_{\rm eff}^{\rm SM} = 3.0440 \pm 0.0002$. We therefore conclude that aforementioned number remains to be the state-of-the-art benchmark for $N_{\rm eff}^{\rm SM}$ in the standard model of particle physics.

Eur. Phys. J. C manuscript No.
(will be inserted by the editor)

Z' boson mass reach and model discrimination at muon colliders

Kateryna Korshynska[a,1,2,3], **Maximilian Löschner**[b,1], **Mariia Marinichenko**[c,1,2,4], **Krzysztof Mękała**[d,1,5], **Jürgen Reuter**[e,1]

[1]Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany
[2]Department of Physics, Taras Shevchenko National University of Kyiv, 64/13, Volodymyrska Street, 01601 Kyiv, Ukraine
[3]Fundamentale Physik für Metrologie FPM, Physikalisch-Technische Bundesanstalt PTB, Bundesallee 100, 38116 Braunschweig, Germany
[4]Instituut-Lorentz, Leiden University, Niels Bohrweg 2, 2333 CA Leiden, The Netherlands
[5]Faculty of Physics, University of Warsaw, Pasteura 5, 02-093 Warszawa, Poland

Received: date / Accepted: date

Abstract We study the discrimination power of future multi-TeV muon colliders for a large set of models with extended gauge symmetries and additional neutral gauge bosons ("Z'-models"). Our study is carried out using a χ^2-analysis of leptonic observables of s-channel scattering in effective Z'-models. We make use of angular and chiral asymmetries induced in such models to find the discovery reach of a given muon collider setup in terms of the Z' mass and to discriminate between the different scenarios. In this context, we discuss how polarized beams – should they become available at muon colliders – or polarization measurements can help in the discrimination. Our results show that typical muon collider setups which are currently under consideration can give a significantly higher reach compared to existing bounds and projections for high-luminosity LHC.

1 Motivation

The Standard Model (SM) of particle physics is among the most well-tested theories to date and can explain experimental observations to unprecedented precision despite thorough searches for deviations at modern collider experiments. Nonetheless, several well-known phenomena such as the nature of dark matter, the baryon-antibaryon asymmetry of the universe or even the universal law of gravity lack an explanation within this theory. To accommodate for effects Beyond the Standard Model (BSM), multiple extensions of the current formulation have been proposed. If such extensions are based on new gauge symmetries, the existence of additional neutral gauge bosons (which we denote as Z') is the natural consequence. In the absence of a unique well-motivated ultra-violet (UV) complete BSM theory, simplified models or effective theories can be useful tools to study potential deviations from SM predictions in a generic way. An example of this is the effective Z'-model with new gauge boson couplings to the SM fermions, as discussed e.g. in [1–3]. The idea is that an experimental determination of such couplings could eventually give guidance toward a specific UV-complete model which in turn might help explain other observational phenomena.

Recent measurements at the LHC have excluded the existence of a Z' boson with a mass up to about 5 TeV [4–11], which will be raised to close to 8 TeV [12]. Several ways to search for neutral gauge bosons have also been considered for future e^+e^- colliders which, mainly due to a cleaner collision environment, could probe masses up to about 20 TeV, depending on the collider energy [2, 13–22]. Given recent progress in the development of the muon collider accelerator design, the possibility of searching for heavy particles at such a multi-TeV machine is an appealing idea and has already been considered in [23] where several resonance production channels have been studied.

A multi-TeV muon collider has been proposed as the next energy-frontier collider in high-energy physics, combining the clean environment of e^+e^- machines with the energy reach of hadron colliders. Recent technological progress, especially in muon cooling [24], has led to a high priority in the US Snowmass Community Summer Study [25–28] and the Particle Physics Project Prioritization Panel (P5) report [29]. In Europe, the International Muon Collider Collaboration (IMCC) is leading the European effort, suggested in the last European Particle Physics Strategy Update (EPPSU 2020) [30, 31].

A comprehensive, systematic study of the indirect discovery reach of future muon colliders for heavy neutral gauge bosons originating from different unification scenar-

[a]*kateryna.korshynska@desy.de*
[b]*maximilian.loeschner@desy.de*
[c]*mariia.marinichenko@desy.de*
[d]*krzysztof.mekala@desy.de*
[e]*juergen.reuter@desy.de*

Prospects for measuring time variation of astrophysical neutrino sources at dark matter detectors

Yi Zhuang,[1] Louis E. Strigari,[1] Lei Jin,[2] and Samiran Sinha[3]

[1]*Department of Physics and Astronomy, Mitchell Institute for Fundamental Physics and Astronomy, Texas A&M University, College Station, Texas 77843, USA*

[2]*Department of Mathematics and Statistics, Texas A&M University-Corpus Christi, Corpus Christi, TX 78412, USA*

[3]*Department of Statistics, Texas A&M University, College Station, Texas 77843, USA*

(Dated: February 29, 2024)

We study the prospects for measuring the time variation of solar and atmospheric neutrino fluxes at future large-scale Xenon and Argon dark matter detectors. For solar neutrinos, a yearly time variation arises from the eccentricity of the Earth's orbit, and, for charged current interactions, from a smaller energy-dependent day-night variation to due flavor regeneration as neutrinos travel through the Earth. For a 100-ton Xenon detector running for 10 years with a Xenon-136 fraction of $\lesssim 0.1\%$, in the electron recoil channel a time-variation amplitude of about 0.8% is detectable with a power of 90% and the level of significance of 10%. This is sufficient to detect time variation due to eccentricity, which has amplitude of $\sim 3\%$. In the nuclear recoil channel, the detectable amplitude is about 10% under current detector resolution and efficiency conditions, and this generally reduces to about 1% for improved detector resolution and efficiency, the latter of which is sufficient to detect time variation due to eccentricity. Our analysis assumes both known and unknown periods. We provide scalings to determine the sensitivity to an arbitrary time-varying amplitude as a function of detector parameters. Identifying the time variation of the neutrino fluxes will be important for distinguishing neutrinos from dark matter signals and other detector-related backgrounds, and extracting properties of neutrinos that can be uniquely studied in dark matter experiments.

I. INTRODUCTION

Over the past several decades, direct dark matter detection experiments have made tremendous progress in constraining weak-scale particle dark matter [1, 2]. Future larger-scale detectors will be sensitive to not only particle dark matter, but also astrophysical neutrinos and various other rare-event phenomenology [3]. The most prominent of the neutrino signals are from the Sun, the atmosphere, and the diffuse supernova neutrino background (DSNB) [4]. Understanding these signals has important implications for the future of particle dark matter searches, but also for understanding the nature of the sources and the properties of neutrinos [5].

Various methods have been proposed to distinguish neutrinos and a possible dark matter signal. These include exploiting the energy distribution of nuclear recoils between neutrinos and dark matter [6, 7], the differences in arrival directions [8], and the differences in the periodicities of the signal [9, 10]. New physics in the neutrino sector may also change the nature of the predicted neutrino signal [11–13], and provide a method to discriminate from dark matter.

Here we examine the time variations of the neutrino signals in more detail and study the prospects for measuring these time variations. For solar neutrinos, the time variation of the flux is due to the eccentricity of the Earth's orbit and the day-night effect. The former is independent of the neutrino flavor, while the latter, which results from neutrino interactions with the matter as they pass through the Earth, is flavor dependent. Both effects are present in a dark matter experiment through the nuclear recoil and electron recoil channels. Beyond solar neutrinos, there may be detectable time variation of other components of the astrophysical neutrino flux. Due to the solar cycle, there is a time variation of the atmospheric neutrino flux which is $\sim 10-30\%$ [14] depending on the detector location. We present the first estimates of the detectability of the time variation of the atmospheric neutrino flux given realistic future detector configurations.

Identifying the time variation for the different neutrino sources is important for properly extracting the signal and distinguishing it from dark matter [4, 15]. In addition, it is important to characterize these signals to constrain neutrino properties. Previous studies of neutrinos in dark matter experiments have only considered the time variation of solar neutrinos as being due to the eccentricity of the Earth's orbit, and for idealistic values of the nuclear recoil threshold [9]. In addition to examining more realistic and updated detector configurations, we consider the prospects for measuring time variation of solar neutrinos using the neutrino-electron elastic scattering channel for the first time.

Solar neutrino experiments have previously searched for time variations in their signals, including experiments that have successfully established time variation due to the eccentricity of the Earth's orbit [16, 17] and the day-night effect [18]. These experiments each used a range of statistical technqiues to identify the time variable signal. As part of our analysis, we rigorously compare the different statistical methodologies for extracting the time-varying signal. We present results for the sensitivity of given experiments to time-varying amplitudes, and quantify the prospects for signal extraction as a function of experimental sensitivity and background levels.

This paper is organized as follows. In Section II, we briefly describe the signals and the models for the detector efficiency. In Section III we describe the periodic signals used in this work, and also we summarize the previous experiments that have searched for neutrino periodicity. Next, in Section IV, we review the statistical methodologies used in our analysis. In Section V, we describe the simulation strategy, compare statistical methods and introduce the signal-to-noise ratio as a convenient estimation tool. Then in Section VI, we present our resulting projections, and in Section VII, the discussion and conclusions.

II. EVENT RATES AT DIFFERENT DETECTORS

A. Theoretical calculation

Figures 1 and 2 show the electron and nuclear recoil spectra for the solar, atmospheric, and DSNB spectra for Xenon and Argon targets. The nuclear recoil spectrum uses the neutral current coherent elastic neutrino-nucleus scattering (CEvNS) channel, and the electron recoil channel uses charged current neutrino-electron elastic scattering (ES). We refer to previous literature for details of these calculations [19]. Here we simply highlight the components of the spectrum as a function of recoil energy to get a sense of the recoil threshold required to detect each component. For Solar neutrinos, we used the high metallicity model for the normalization [20]. We also show the appropriate experimental background components [21].

In addition to the energy dependence shown in Figure 1 and 2, for several of the neutrino components there is a time variation to the flux. For solar neutrinos, since the time variation due to the eccentricity of the Earth's orbit affects all flavors, it will be present in both the CEvNS and the ES channels. For charged current detection channels, the day-night effect due to oscillations is present in the ES channel. For atmospheric neutrinos, the time variation from the solar modulation of the atmospheric neutrino

Imprints of new physics operators in the semileptonic $B \to a_1(1260)\ell^- \bar{\nu}_\ell$ process in SMEFT approach

Manas Kumar Mohapatra[1],[*] Dhiren Panda[1],[†] and Rukmani Mohanta[1‡]

[1]*School of Physics, University of Hyderabad, Hyderabad - 500046, India*

Abstract

At present, there are several measurements of B decays that exhibit discrepancies with the predictions of the Standard Model, and suggest the presence of new physics in $b \to s$ and $b \to c(u)$ quark level transitions. Motivated by the prospects of the ongoing high-luminosity B factories, we study the exclusive $B \to a_1(1260)\ell^- \bar{\nu}_\ell$ process within the Standard Model Effective Field Theory (SMEFT) formalism, to understand the sensitivity of new physics. The new physics parameters are constrained by using the experimental branching fractions of the (semi)leptonic $B \to \ell\bar{\nu}$ and $B \to (\pi, \rho, \omega)\ell\bar{\nu}$ processes (where $\ell = e, \mu, \tau$) which undergo $b \to u\ell\bar{\nu}$ quark level transitions. We then perform a comprehensive angular analysis of the exclusive $B \to a_1(1260)\ell^- \bar{\nu}_\ell$ process in the Standard Model and in the presence of various new physics operators. We also provide the predictions and comment on various observables, such as branching ratio, forward-backward asymmetry, and the test of lepton flavor non universality of the $B \to a_1(1260)\ell^- \bar{\nu}_\ell$ channel.

[*]Electronic address: manasmohapatra12@gmail.com

[†]Electronic address: pandadhiren530@gmail.com

[‡]Electronic address: rmsp@uohyd.ac.in

Photon quantum kinetic equations and collective modes in an axion background

Marc Comadran[1,2,3*] and Cristina Manuel[1,2†]

[1] *Instituto de Ciencias del Espacio (ICE, CSIC) C. Can Magrans s.n., 08193 Cerdanyola del Vallès, Spain and*

[2] *Institut d'Estudis Espacials de Catalunya (IEEC), Ed. RDIT, Campus UPC, 08860 Castelldefels (Barcelona), Spain and*

[3] *Departament de Física Quàntica i Astrofísica and Institut de Ciències del Cosmos, Universitat de Barcelona (IEEC-UB), Martí i Franqués 1, 08028 Barcelona, Spain*

(Dated: February 29, 2024)

We develop a quantum kinetic theory for photons in the presence of an axion background and in the collisioness limit. In deriving the classical regime of our quantum kinetic equations, we observe that they capture well known features of axion electrodynamics. By projecting the Wigner function onto a polarization basis, relating the Wigner matrix function with the Stokes parameters, we establish the dispersion relations and transport equations for each polarization space component. Additionally, we investigate how the axion background affects the dispersion relations of photon collective modes within an electron-positron plasma at equilibrium temperature T. While the plasmon remains unaffected, we find that the axion background breaks the degeneracy of transverse collective modes at order $eg_{a\gamma}T(\partial a)$, where e represents the electron charge, $g_{a\gamma}$ denotes the photon-axion coupling, and ∂a represents the scale associated with variations in the axion field.

* mcomadca60@alumnes.ub.edu

† cmanuel@ice.csic.es

PROCEEDINGS OF SCIENCE

Ultra-light Dark Matter Search with Astrophysical Neutrino Flavour

Carlos A. Argüelles,[a] **Kareem Farrag**[b] **and Teppei Katori**[c,*]

[a] *Harvard University, Department of Physics and Laboratory for Particle Physics and Cosmology, Cambridge, MA 02138, USA*

[b] *Chiba University, Department of Physics and Institute for Global Prominent Research, Chiba, 263-8522, Japan*

[b] *King's College London, Department of Physics, London, WC2R 2LS, UK*

E-mail: carguelles@g.harvard.edu, k.r.h.farrag@chiba-u.jp, teppei.katori@kcl.ac.uk

The ultra-light dark matter is a new class of dark matter candidates. Unlike traditional dark matter particle candidates, the ultra-light dark matter behaves like a classical field, which saturates the entire Milky Way galaxy with a coherent oscillation. If such dark matter exists and couples with neutrinos, properties of astrophysical neutrinos propagating in the Milky Way would be modified and detectable by neutrino telescopes such as IceCube. Meantime, IceCube looked for quantum-gravity-motivated effects from the astrophysical neutrino flavour information. IceCube did not find evidence of new physics, and they set limits on neutrino - Lorentz violating field couplings. Here, we investigate if these results can be applied to limit the ultra-light dark matter couplings with neutrinos. It is found that the strong limits of neutrino-dark matter couplings in low dark matter mass regions can be obtained in this approach.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

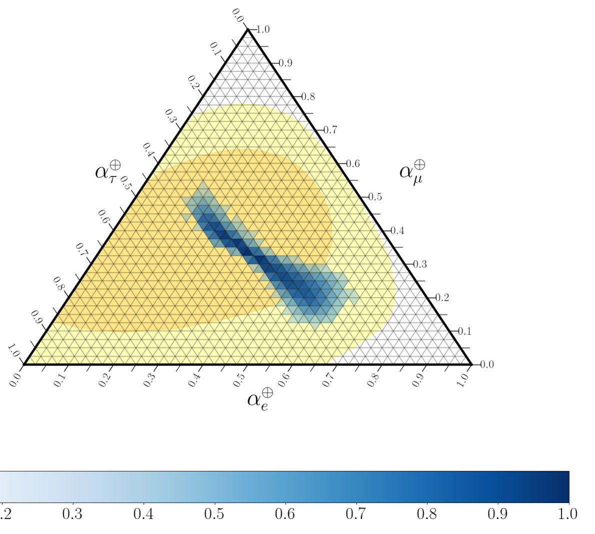

Figure 1: Astrophysical neutrino flavour without new physics. Each point in this figure is the flavour ratio of astrophysical neutrinos at detection. The histogram is the expected flavour ratio for the standard neutrino model with the standard astrophysical neutrino production scenarios, and it is enclosed by the 68% and 95% contours from the IceCube data [7].

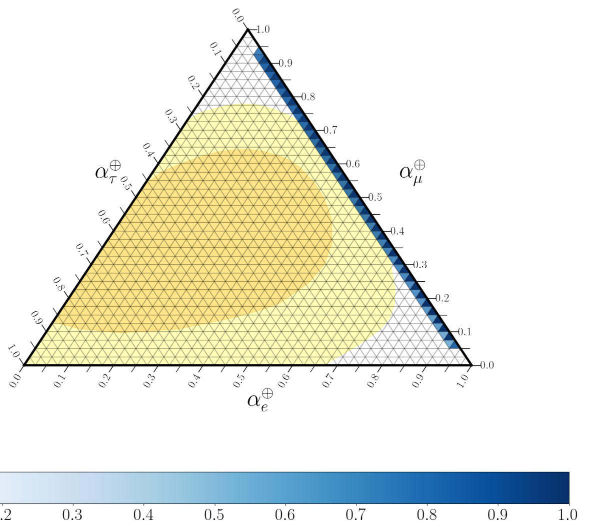

Figure 2: Astrophysical neutrino flavour with static dark matter potential, $g_\tau\sqrt{2\rho}/m_a = 2\times 10^{-26}$ GeV. The value of dark matter is chosen because this value was rejected from the IceCube Lorentz violation analysis [1]. Unlike Fig. 1, predicted astrophysical neutrino flavour is mostly outside of the 68% and 95% data contours [7].

shape in Fig. 1 to a line on the right side, and most of the points go to the outside of the data contours. This is consistent that a precise analysis found that this scenario is rejected in the IceCube with Bayes factor > 10.

In terms of ultra-light dark matter, Eq. 2, Fig. 2 corresponds to the presence of neutrino - dark

The collisional energy loss of a heavy-quark in a semi-quark-gluon plasma

Qianqian Du[a,b], Mudong Du[a], and Yun Guo[a,b,*]
[a] *Department of Physics, Guangxi Normal University, Guilin, 541004, China*
[b] *Guangxi Key Laboratory of Nuclear Physics and Technology, Guilin, 541004, China*

By utilizing a background field effective theory, we compute the collisional energy loss of a heavy-quark moving through a semi-quark-gluon plasma characterized by nontrivial holonomy for Polyakov loops. We consider the elastic scatterings between the incident heavy-quark and the thermal partons with both hard and soft momentum transfers. Our results show that the heavy-quark energy loss is significantly suppressed in the semi-quark-gluon plasma due to a background field that is self-consistently generated in the effective theory. On the other hand, the suppression strongly depends on the temperature of the plasma which becomes negligible above $2 \sim 3$ times the critical temperature. For a realistic coupling constant, ignoring a relatively weak dependence on the heavy-quark velocity, the suppression on the collisional energy loss can be approximated by an overall factor determined solely by the background field.

I. INTRODUCTION

Under extremely hot and dense conditions created in the heavy-ion experiments, the confined states of hadrons are broken, resulting in a new state of matter known as quark-gluon plasma (QGP) [1, 2]. Studying the equation of state is a crucial aspect of understanding the physical properties of the strongly interacting matter. At asymptotically high temperatures, perturbative QCD works very well. Especially, the hard-thermal-loop (HTL) resummed perturbation theory is believed to be a powerful tool which provides reliable predictions on the thermodynamics of the QGP down to several times the critical temperature T_d [3, 4]. On the other hand, the hadron resonance gas model can be used to simulate the confined hadronic phase at temperatures below T_d. However, there exists an intermediate region termed as semi-QGP [5], from the critical temperature to a few times that, where the physics is of particular interest. For high energy heavy-ion experiments carried out at the Large Hadron Collider (LHC), and especially at Relativistic Heavy Ion Collider (RHIC), the temperatures probed are not far from the critical temperature. Unfortunately, neither the hadron resonance gas nor the HTL resummed perturbation theory can be a reliable theoretical means to explore this intermediate region.

The partial deconfinement in a semi-QGP is characterized by nontrivial holonomy for Polyakov loops. As the order parameter for the deconfining phase transition in $SU(N)$ gauge theories, the Polyakov loop is non-zero but less than unity in the semi-QGP region according to the Lattice simulations [6, 7]. This behavior can be realized by introducing a classical background field for the time-like component of the vector potential A_0. The resulting matrix models [8, 9], which can be considered as a background field effective theory, give rise to a deconfining phase transition through a competition between two different contributions making up the effective potential in this model. One is a perturbative term, favoring the completely deconfined vacuum, and the other is a non-perturbative term, driving the system to confinement. In addition, the predicted thermodynamics is also in a good agreement with the Lattice data. Given the success made by the matrix models, it is reasonable to adopt such an effective theory to study some other physical quantities in a semi-QGP.

In this work, we will focus on the collisional energy loss $-dE/dx$ of an energetic heavy-quark moving through a hot and dense QCD plasma which is only partially deconfined. As observed in the relativistic heavy-ion experiments, the suppression of high transverse momentum hadrons can be explained by the energy loss of high energy partons in the plasma. This phenomenon is called the jet quenching, an excellent hard probe which provides a novel window to unravel the fascinating properties of the deconfined nuclear matter [10–13]. Furthermore, unlike the light quarks which lose energy mainly through the gluon radiation, the collisional energy loss of a heavy-quark is comparable to the radiated energy loss because of the dead-cone effect related to the large quark mass [14–17]. Therefore, investigating the collisional energy loss induced by the elastic scatterings between the incident heavy-quark and thermal medium partons can help us to understand the measured heavy-flavor spectra in nucleus-nucleus collisions. After the first detailed calculation of $-dE/dx$ for a heavy-quark in the QCD plasma made by Braaten and Thoma [18, 19], many attentions have been paid to this research topic and there were various theoretical developments over the past thirty years, see [20–30] and references therein.

[*] Corresponding author: yunguo@mailbox.gxnu.edu.cn

All-heavy pentaquarks in a nonrelativistic potential quark model

Zhi-Biao Liang[1], Feng-Xiao Liu[2,3] *, and Xian-Hui Zhong[1,3] †
1) Department of Physics, Hunan Normal University, and Key Laboratory of Low-Dimensional Quantum Structures and Quantum Control of Ministry of Education, Changsha 410081, China
2) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China and
3) Synergetic Innovation Center for Quantum Effects and Applications (SICQEA), Hunan Normal University, Changsha 410081, China

In a nonrelativistic potential quark model framework, we carry out a serious calculation of the all-heavy pentaquarks by adopting the explicitly correlated Gaussian method. A complete mass spectrum for the $1S$ states is obtained. For the $cccc\bar{c}$, $cccc\bar{b}$, $bbbb\bar{c}$, $bbbb\bar{b}$, $ccbb\bar{c}$, and $bbcc\bar{b}$ systems, the obtained states are compact and lie far above the lowest dissociation baryon-meson threshold. While, in the $cccb\bar{c}$, $cccb\bar{b}$, $bbbc\bar{c}$, and $bbbc\bar{b}$ systems with $\{123\}4\bar{5}$ symmetry, the two low-lying configurations with $J^P = 5/2^-$ and $3/2^-$ have a typical molecular structure due to the special role of the color-Coulomb interactions, they may be good candidates of stable states below the dissociation baryon-meson thresholds.

I. INTRODUCTION

Searching for genuine exotic multiquark states beyond the conventional meson ($q\bar{q}$) and baryon (qqq) states has been one of the most important initiatives since the establishment of quark model in 1964 [1–3]. Since the discovery of $X(3872)$ by Belle in 2003 [4], many tetraquark candidates, such as the series hidden-charmed/bottom XYZ states [5], the doubly-charmed state $T_{cc}(3875)^+$ [6, 7], and charmed-strange states [8, 9], have been observed in experiments. Furthermore, the exotic P_c [10–12] and P_{cs} [13] states as candidates of pentaquark states were also reported by the LHCb collaboration. All of these observed exotic states contains two or three light quarks, it is very difficult to determine whether they are hadronic molecular states or genuine multiquark states due to the role of light-meson exchanges. This dilemma should be largely alleviated for the all-heavy multiquarks. They are most likely to be genuine multiquark states since there is no light-meson exchange potential, which is often needed by the formation molecules. Thus, the study of the all-heavy multiquarks may provide an interesting way for establishing the genuine multiquark states.

Impressively, some all-heavy multiquark states have been observed in LHC experiments. In 2020, the LHCb Collaboration observed a narrow structure $X(6900)$ together a broad structure ranging from 6.2 to 6.8 GeV in the di-J/ψ invariant mass spectrum [14]. Later in 2022, the $X(6900)$ was confirmed in the same final state by both the ATLAS [15] and CMS [16] collaborations. Moreover, in the lower mass region the CMS measurements show that a clear resonance $X(6600)$ lies in the di-J/ψ spectrum. These clear structures may be evidences for genuine all-charmed tetraquark $cc\bar{c}\bar{c}$ states. The discovery of $cc\bar{c}\bar{c}$ states has demonstrated the powerful abilities of LHC in productions of fully-heavy hadrons, and also indicates that the all-heavy pentaquark should be exist. Thus, one may expect to observe some all-heavy pentaquarks in forthcoming experiments.

Stimulated by these, some relative studies of the all-heavy pentaquarks have been carried out within various models in recent years. The all-charmed and -bottom pentaquarks were studied with the QCD sum rules [17, 18]. For the baryon-meson type, the masses of $cccc\bar{c}$ and $bbbb\bar{b}$ are predicted to be $\sim$ 7.41 GeV and $\sim$ 21.60 GeV, respectively in Ref. [17], which are notably smaller than those of 7.93 ± 0.15 GeV and 23.91 ± 0.15 GeV predicted for the diquark-diquark-antiquark type in Ref. [18]. In Ref. [19], the mass spectra of the $1S$-wave all-heavy pentaquarks were systematically studied with the simple chromomagnetic interaction (CMI) model. The masses of $cccc\bar{c}$ and $bbbb\bar{b}$ are predicted to be $\sim$ 7.9 GeV and $\sim$ 23.8 GeV, respectively, which are slightly above the lowest dissociation baryon-meson mass threshold. While, there may exist a stable $J^P = 3/2^-$ $bbcc\bar{b}$ states with a mass of $\sim$ 17.4 MeV. In Ref. [20], the all-heavy pentaquarks were further studied within the MIT bag model by including the chromomagnetic interaction. In this framework, the masses of $cccc\bar{c}$ and $bbbb\bar{b}$ are predicted to be $\sim$ 8.2 GeV and $\sim$ 24.8 GeV, and no stable states below the dissociation baryon-meson thresholds are found.

In the recent two years, the all-heavy pentaquarks have been studied with more comprehensive potential quark models, where besides the chromomagnetic interaction, the confining and Coulomb-like potentials are also included in the calculations. In Refs. [21, 22], the authors studied the all-heavy pentaquarks by using the resonating group method (RGM), in which two-cluster approximation is adopted. They obtained one possible stable $J^P = 1/2^-$ $cccc\bar{c}$ state with a mass of $\sim$ 7.9 GeV, and two possible stable $bbbb\bar{b}$ states with $J^P = 1/2^-$ and $J^P = 3/2^-$ in the mass range of $\sim$ 23.8 GeV, and several possible stable candidates in the charmed-bottom pentaquarks. In Ref. [23], considering the baryon-meson and diquark-diquark-antiquark configurations, the authors obtained several narrow resonances above 8.0 GeV and 24.0 GeV for the $cccc\bar{c}$ and $bbbb\bar{b}$ pentaquarks, respectively, based on the Gaussian expansion method combined with a complex-scaling range approach. Recently, a more serious dynamical calculation beyond the cluster approximation has been carried out by using the variational method with the trial spatial wave function in a simple Gaussian form [24]. No stable pentaquarks states below the dissociation baryon-meson thresholds are found. The masses for the ground $cccc\bar{c}$ and $bbbb\bar{b}$ states are predicted

*E-mail: liufx@ihep.ac.cn
†E-mail: zhongxh@hunnu.edu.cn

Nucleons and vector mesons in a confining holographic QCD model

Alfonso Ballon-Bayona,[a] **Adão S. da Silva Junior**[a]

[a] *Instituto de Física, Universidade Federal do Rio de Janeiro, Caixa Postal 68528, RJ 21941-972, Brazil.*

E-mail: aballonb@if.ufrj.br, adaossj@pos.if.ufrj.br

Abstract: We present a simple holographic QCD model that provides a unified description of vector mesons and nucleons in a confining background based on Einstein-dilaton gravity. For the confining background we consider analytical solutions of the Einstein-dilaton equations where the dilaton is a quadratic function of the radial coordinate far from the boundary. We build actions for the 5d gauge field and the 5d Dirac field dual to the 4d flavor current and the 4d nucleon interpolator respectively. In order to obtain asymptotically linear Regge trajectories we impose for each sector the condition that the effective Schrödinger equation has a potential that grows quadratically in the radial coordinate far from the boundary. For the vector mesons we show that this condition is automatically satisfied by a 5d Yang-Mills action minimally coupled to the metric and the dilaton. For the nucleons we find that the mass term of the 5d Dirac action needs to be generalised to include couplings to the metric and the dilaton. Using Sturm-Liouville theory we obtain a spectral decomposition for the hadronic correlators consistent with large N_c QCD. Our setup contains only three parameters: the mass scale associated with confinement, the 5d gauge coupling and the 5d Dirac coupling. The last two are completely fixed by matching the correlators at high energies to perturbative QCD. We calculate masses and decay constants and compare our results against available experimental data. Our model can be thought of as a consistent embedding of soft wall models in Einstein-dilaton gravity.

OU-HEP-240301

Weak scale supersymmetry emergent from the string landscape

Howard Baer[1*], Vernon Barger[2†], Dakotah Martinez[1§] and Shadman Salam[3§]

[1]Homer L. Dodge Department of Physics and Astronomy,
University of Oklahoma, Norman, OK 73019, USA
[2]Department of Physics, University of Wisconsin, Madison, WI 53706 USA
[3]Department of Mathematics and Natural Sciences, Brac University, Dhaka 1212, Bangladesh

Abstract

Superstring flux compactifications can stabilize all moduli while leading to an enormous number of vacua solutions, each leading to different $4-d$ laws of physics. While the string landscape provides at present the only plausible explanation for the size of the cosmological constant, it may also predict the form of weak scale supersymmetry which is expected to emerge. Rather general arguments suggest a power-law draw to large soft terms, but these are subject to an anthropic selection of not-too-large a value for the weak scale. The combined selection allows one to compute relative probabilities for the emergence of supersymmetric models from the landscape. Models with weak scale naturalness appear most likely to emerge since they have the largest parameter space on the landscape. For finetuned models such as high scale SUSY or split SUSY, the required weak scale finetuning shrinks their parameter space to tiny volumes, making them much less likely to appear compared to natural models. Probability distributions for sparticle and Higgs masses from natural models show a preference for Higgs mass $m_h \sim 125$ GeV with sparticles typically beyond present LHC limits, in accord with data. From these considerations, we briefly describe how natural SUSY is expected to be revealed at future LHC upgrades. This article is a contribution to the Special Edition of the journal *Entropy* honoring Paul Frampton on his 80th birthday.

*Email: baer@ou.edu
†Email: barger@pheno.wisc.edu
§Email: dakotah.s.martinez-1@ou.edu
§Email: ext.shadman.salam@bracu.ac.bd

Flavor-Violating ALPs, Electron $g-2$, and the Electron-Ion Collider

Hooman Davoudiasl*,[1] Roman Marcarelli†,[1,2] and Ethan T. Neil‡[2]

[1]*High Energy Theory Group, Physics Department, Brookhaven National Laboratory, Upton, NY 11973, USA*

[2]*Department of Physics, University of Colorado, Boulder, Colorado 80309, USA*

We revisit the possibility that light axion-like particles (ALPs) with lepton flavor violating couplings could give significant contributions to the electron's anomalous magnetic moment g_e-2. Unlike flavor diagonal lepton-ALP couplings, which are exclusively axial, lepton flavor violating couplings can have arbitrary chirality. Focusing on the e-τ ALP coupling, we find that the size of the contribution to g_e-2 depends strongly on the chirality of the coupling. A significant part of the parameter space for which such a coupling can explain experimental anomalies in g_e-2 can be probed at the Electron-Ion Collider, which is uniquely sensitive to the chirality of the coupling using the polarization of the electron beam.

I. INTRODUCTION

Axion-like particles (ALPs) are a generic type of new particle that can occur in a wide variety of scenarios for physics beyond the Standard Model (BSM). Such particles commonly arise as pseudo-Nambu-Goldstone bosons associated with new physics [1, 2]. Their pseudo-Goldstone nature means that ALPs can naturally be very light compared to the scale of new physics, with very weak interactions suppressed by the same large mass scale.

Within the general theory space, an intriguing possibility is the presence of significant lepton-flavor-violating (LFV) couplings for an ALP. Lepton flavor is almost perfectly conserved in the Standard Model (SM), up to neutrino flavor mixing, so that lepton flavor violation is a sensitive probe of new physics. At the same time, existing anomalies in precision lepton physics, in particular in the anomalous magnetic moments of the electron and muon, motivate the exploration of new particles coupled to leptons. Previous studies of the phenomenology of LFV ALPs include [3–12].

While there is significant attention on present tensions between theory and experiment in the anomalous magnetic moment of the muon [13], the anomalous magnetic moment of the electron g_e-2 is also showing possible tensions with the SM, although the situation is somewhat less clear. The latest measurement of g_e-2 [14] is in tension with the SM prediction of either $+2.2\sigma$ or -3.7σ [15], depending on whether the fine-structure constant α obtained from Rb [16] or Cs [17] is used as input.

Contributions from lepton-flavor violating ALP couplings to g_e-2 have been calculated and studied in the literature previously [5, 6, 10]. In this work, we focus on the interplay between the magnitude of the e-τ ALP coupling and its chirality, which has a significant impact on the g_e-2 contribution. We find a substantial region of parameter space where a single e-τ coupling with a GeV-scale ALP and the correct chirality can explain the current experimental anomalies in g_e-2 without being constrained by other experiments, but with discovery potential in future searches at the EIC [9]. The EIC is also uniquely well-equipped to probe the chiral structure of such a coupling directly by utilizing the polarization of its electron beam.

II. MODEL SETUP

We will consider an ALP-e-τ interaction of the form

$$\mathcal{L}_{\rm int} = \frac{\partial_\mu a}{\Lambda}\bar{\tau}\gamma^\mu\left(V_{\tau e} + A_{\tau e}\gamma_5\right)e + \text{H.C.}, \qquad (1)$$

where $V_{\tau e}$ and $A_{\tau e}$ are complex constants in general. We can decompose this term into a more useful form by defining

$$\begin{aligned} \phi_V &\equiv \arg V_{\tau e}, & \phi_A &\equiv \arg A_{\tau e} \\ \phi &\equiv \phi_A - \phi_V, & \tan\theta &\equiv \left(|V_{\tau e}|/|A_{\tau e}|\right), \\ C_{\tau e} &\equiv \sqrt{|A_{\tau e}|^2 + |V_{\tau e}|^2}. \end{aligned} \qquad (2)$$

Then, the interaction can be written as

$$\mathcal{L}_{\rm int} = \frac{C_{\tau e}e^{i\phi_V}}{\Lambda}\partial_\mu a\,\bar{\tau}\gamma^\mu\left(\sin\theta + e^{i\phi}\cos\theta\gamma_5\right)e + \text{H.C.} \qquad (3)$$

Note that if the coupling were lepton flavor diagonal, hermiticity would require $\theta = \phi_A = \phi_V = 0$. Hence, the presence of flavor violation allows for both parity (P) violation (via θ) and charge/parity (CP) violation (via ϕ and ϕ_V). The overall phase ϕ_V does not contribute to any of the physical processes we consider below.

For simplicity, we will study the case in which the only significant coupling is $C_{\tau e}$. As explored in Ref. [8], other bounds from precision flavor physics are relevant for ALPs heavier than m_τ only when lepton-flavor diagonal couplings are also present and sufficiently strong.

*email: hooman@bnl.gov

†email: roman.marcarelli@colorado.edu

‡email: ethan.neil@colorado.edu

An Axion Pulsarscope

Mariia Khelashvili,[1, 2, 3, *] Mariangela Lisanti,[1, 4, †] Anirudh Prabhu,[5, ‡] and Benjamin R. Safdi[6, 7, §]

[1] *Department of Physics, Princeton University, Princeton, NJ 08544, USA*
[2] *Bogolyubov Institute for Theoretical Physics of the NAS of Ukraine, Metrolohichna Str. 14-b, Kyiv, 03143, Ukraine*
[3] *Goethe Universität, Max-von-Laue Str. 1, Frankfurt am Main, 60438, Germany*
[4] *Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*
[5] *Princeton Center for Theoretical Science, Princeton University, Princeton, NJ 08544, USA*
[6] *Berkeley Center for Theoretical Physics, University of California, Berkeley, CA 94720, USA*
[7] *Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

(Dated: February 29, 2024)

Electromagnetic fields surrounding pulsars may source coherent ultralight axion signals at the known rotational frequencies of the neutron stars, which can be detected by laboratory experiments (*e.g.*, pulsarscopes). As a promising case study, we model axion emission from the well-studied Crab pulsar, which would yield a prominent signal at $f \approx 29.6$ Hz regardless of whether the axion contributes to the dark matter abundance. We estimate the relevant sensitivity of future axion dark matter detection experiments such as DMRadio-GUT, Dark SRF, and CASPEr, assuming different magnetosphere models to bracket the uncertainty in astrophysical modeling. For example, depending on final experimental parameters, the Dark SRF experiment could probe axions with any mass $m_a \ll 10^{-13}$ eV down to $g_{a\gamma\gamma} \sim 3 \times 10^{-13}$ GeV^{-1} with one year of data and assuming the vacuum magnetosphere model. These projected sensitivities may be degraded depending on the extent to which the magnetosphere is screened by charge-filled plasma. The promise of pulsar-sourced axions as a clean target for direct detection experiments motivates dedicated simulations of axion production in pulsar magnetospheres.

Introduction.— The existence of axions is predicted by numerous well-motivated extensions to the Standard Model [1, 2]. While interesting in their own right, these ultralight pseudoscalar bosons can potentially account for the dark matter (DM), as is the case for the quantum chromodynamics (QCD) axion [3–10]. Given their ubiquity in theoretical models, a broad laboratory program exists to search for axions (see [11–13]). This includes haloscope experiments, which search for axion DM in the Milky Way [14–28], helioscope experiments, which search for axions produced by the Sun [29, 30], and "light shining through walls" experiments, which aim to produce axions directly in the lab [31, 32]. This Letter proposes a fourth alternative—the *pulsarscope*—and demonstrates that planned experiments can successfully search for coherent axion signals emitted by nearby pulsars.

Axions are generically expected to couple to Standard Model fields through dimension-five operators, motivating efforts to detect them in the laboratory. For example, the axion field, $a(x)$, couples to electromagnetism through the operator $\mathcal{L} \supset -g_{a\gamma\gamma} a F\tilde{F}/4 = g_{a\gamma\gamma} a \mathbf{E}\cdot\mathbf{B}$, where $g_{a\gamma\gamma}$ is the coupling constant, F is the quantum electrodynamics (QED) field strength, and $\mathbf{E}$ ($\mathbf{B}$) is the electric (magnetic) field. The axion may also couple to Standard Model fermions f through the operator $\mathcal{L} \supset (g_{aff}/2m_f)\partial_\mu a \bar{f}\gamma^\mu\gamma^5 f = -(g_{aff}/m_f)\boldsymbol{\nabla} a \cdot \mathbf{S}$ (in the non-relativistic limit), where $\mathbf{S}$ is the fermion spin operator, m_f is the fermion mass, and g_{aff} is the coupling constant. These operators may induce observable signatures in laboratory experiments, such as axion-to-photon conversion (*e.g.*, [29, 30, 33–38]) or spin precession (*e.g.*, [39–45]).

Rapidly-rotating neutron stars (NSs), or pulsars, can serve as axion factories because their magnetospheres may possess regions of large, un-screened accelerating electric fields ($\mathbf{E}\cdot\mathbf{B} \neq 0$) [46–48]. In non-axisymmetric pulsar magnetospheres, ultralight axions are efficiently radiated at the rotation frequency of the pulsar, Ω [46]. As illustrated in Fig. 1, this relativistic axion signal travels towards Earth, where it may be detected by a ground-based experiment. While their densities are generally much smaller than the DM density near Earth [12], pulsar-sourced axions benefit from large coherence times and have known frequencies.

We estimate the sensitivity of proposed axion DM detection experiments to pulsar-sourced axions. We consider two extreme models of the pulsar magnetosphere to bracket the uncertainty on the expected signal. The leading sensitivity to low-mass axions is obtained from the CASPEr-wind [40–43], Dark SRF [49, 50], and DMRadio-GUT [51, 52] experiments. Most optimistically, these experiments could probe previously unexplored regions of axion parameter space for axion masses $m_a \ll 10^{-13}$ eV; however, if the magnetospheres are heavily screened, then the sensitivities may be subdominant relative to current constraints.

Axion Radiation from Pulsars.— The axion field sourced by a pulsar is determined by the distribution of $\mathbf{E}\cdot\mathbf{B}$ in the magnetosphere according to the Klein-Gordon equation, $(\Box + m_a^2)a(x) = g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}$. In the limit where the axion mass $m_a \to 0$, this equation is analogous to that for the electric potential, interpreted as $a(x)$, in Lorenz gauge with charge density $\rho_{\rm eff} = g_{a\gamma\gamma}\mathbf{E}\cdot\mathbf{B}$. Thus, one can calculate the radiated axion signal given a model