arXiv:2403.03147v1 [gr-qc] 5 Mar 2024

The resonant history of gravitational atoms in black hole binaries

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Abstract

Rotating black holes can produce superradiant clouds of ultralight bosons. When the black hole is part of a binary system, its cloud can undergo resonances and ionization. These processes leave a distinct signature on the gravitational waveform that depends on the cloud's properties. To determine the state of the cloud by the time the system enters the band of future millihertz detectors, we study the chronological sequence of resonances encountered during the inspiral. For the first time, we consistently take into account the nonlinearities induced by the orbital backreaction and we allow the orbit to have generic eccentricity and inclination. We find that the resonance phenomenology exhibits striking new features. Resonances can "start" or "break" above critical thresholds of the parameters, which we compute analytically, and induce dramatic changes in eccentricity and inclination. Applying these results to realistic systems, we find two possible outcomes. If the binary and the cloud are sufficiently close to counter-rotating, the cloud survives in its original state until the system enters in band; otherwise, the cloud is destroyed during a resonance at large separations, but leaves an imprint on the eccentricity and inclination. In both scenarios, we characterize the observational signatures, with particular focus on future gravitational wave detectors.

arXiv:2403.03106v1 [gr-qc] 5 Mar 2024

Understanding gravitationally induced decoherence parameters in neutrino oscillations using a microscopic quantum mechanical model

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Abstract

In this work, a microscopic quantum mechanical model for gravitationally induced decoherence introduced by Blencowe and Xu is investigated in the context of neutrino oscillations. The focus is on the comparison with existing phenomenological models and the physical interpretation of the decoherence parameters in such models. The results show that for neutrino oscillations in vacuum gravitationally induced decoherence can be matched with phenomenological models with decoherence parameters of the form $\boldsymbol{\Gamma_{ij} \sim \Delta m^4_{ij} E^{-2}}$. When matter effects are included, the decoherence parameters show a dependence on matter effects, which vary in the different layers of the Earth, that can be explained with the form of the coupling between neutrinos and the gravitational wave environment inspired by linearised gravity. Consequently, in the case of neutrino oscillations in matter, the microscopic model does not agree with many existing phenomenological models that assume constant decoherence parameters in matter, and their existing bounds cannot be used to further constrain the model considered here. The probabilities for neutrino oscillations with constant and varying decoherence parameters are compared and it is shown that the deviations can be up to 10%. On a theoretical level, these different models can be characterised by a different choice of Lindblad operators, with the model with decoherence parameters that do not include matter effects being less suitable from the point of view of linearised gravity.

Keywords: decoherence, neutrino oscillations, gravity, open quantum systems

1 Introduction

The search for quantum decoherence (QD) effects in connection with neutrino oscillations is a topic that has gained increasing interest in various research communities in recent years [1–32]. Neutrino experiments have searched for QD effects on current data via a phenomenological approach [21–25] and several works have analysed the sensitivity of future detectors [19, 33]. However, the connection between such phenomenological models and the underlying microscopic physics is not always immediate. It is interesting to understand, in terms of theoretical models in the framework of open quantum systems [34], how the phenomenological models used for neutrino oscillations can be derived from underlying microscopic physics.

arXiv:2403.03004v1 [astro-ph.CO] 5 Mar 2024

Ultralight vector dark matter search using data from the KAGRA O3GK run

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arXiv:2403.02980v1 [hep-th] 5 Mar 2024

Fermionic Fixed-Point Structure of Asymptotically Safe QED with a Pauli Term

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(Dated: March 6, 2024)

We test the physical viability of a recent proposal for an asymptotically safe modification of quantum electrodynamics (QED), whose ultraviolet physics is dominated by a non-perturbative Pauli spin-field coupling. We focus in particular on its compatibility with the absence of dynamical generation of fermion mass in QED. Studying the renormalization group flow of chiral four-fermion operators and their fixed points, we discover a distinct class of behavior compared to the standard picture of fixed-point annihilation at large gauge couplings and the ensuing formation of chiral condensates. Instead, transcritical bifurcations, where the fixed points merely exchange infrared stability, are observed. Provided that non-chiral operators remain irrelevant, our theory accommodates a universality class of light fermions for $N_\mathrm{f} > 1$ irreducible Dirac flavors. On the contrary, in the special case of $N_\mathrm{f} = 1$ flavor, this comes only at the expense of introducing one additional relevant parameter.

I. INTRODUCTION

Quantum electrodynamics (QED) is an extremely well-tested theory, exhibiting remarkable agreement with precision experiments at low energies [1–5]. Of course, high-energy tests are also passed by the theory though at lower precision [6, 7] and ultimately require the embedding of QED into the electroweak sector of the standard model. Still, the high-energy behavior of pure QED remains of interest in its own right, as it has constituted a puzzle since the early days of quantum field theory: perturbation theory predicts a divergence of the minimal gauge coupling at a finite Landau pole [8, 9]. While this may simply signal the expected breakdown of perturbation theory in the strong-coupling regime, the conclusion of the existence of a finite scale of maximum ultraviolet (UV) extension is supported by lattice simulations [10–12] and functional methods [13].

The picture obtained from such nonperturbative methods is, however, decisively different from simple perturbation theory: a strong coupling phase of QED – even if it existed – can generically not be connected by a line of constant physics to physical QED because of chiral symmetry breaking. Strong gauge interactions induce fermion mass generation with masses on the order of the high scale being incompatible with the observed existence of a light electron. In continuum computations, the symmetry breaking can be traced back to fermionic self-interactions turning into relevant operators at strong coupling and triggering condensate formation [13–15]. The corresponding long-range limit of such a theory would then be a free photon theory.

As a resolution, a recent proposal has been based on the observation that the Pauli spin-field coupling term $\bar{\psi}\sigma_{\mu\nu}F^{\mu\nu}\psi$ has the potential to screen the Landau pole – and thus the strong-coupling regime – within an effective field theory [16]. In fact, a self-consistent analysis of pure QED with a Pauli term has provided evidence for the existence of interacting fixed-points potentially rendering QED asymptotically safe [17, 18] and thus high-energy complete. As a dimension-5 operator with only a single derivative with respect to the photon, the Pauli term represents the unique next-to-leading-order contribution in a combined derivative and power-counting operator expansion of the effective action.

By the techniques of functional renormalization, the extended theory space has been shown to include two non-trivial fixed points $\mathcal{B}$ and $\mathcal{C}$ at vanishing gauge coupling [17], each of which provides an ultraviolet (UV) completion of QED as an asymptotic safety scenario. Specifically, the fixed point $\mathcal{C}$ occurring at a finite Pauli coupling κ is compatible with a renormalization group (RG) trajectory reproducing the long-range values of phenomenological QED. As it features three relevant directions, the long-range physics is fully predictive, once three parameters have been fixed by experiment (e.g., the electron mass, the fine structure constant, and the anomalous magnetic moment of the electron). (By contrast, fixed point $\mathcal{B}$ predicts unphysically large values of the anomalous magnetic moment in the infrared (IR); while being potentially consistent and UV complete, this universality class is observationally not viable.)

In view of the impossibility to connect conventional strong-coupling QED with the observed existence of light electrons, an obvious question needs to be answered: does an asymptotically safe UV completion based on the Pauli term preserve chiral symmetry along its RG trajectories towards the infrared (IR)? This is not at all evident, since fixed point $\mathcal{C}$ – though featuring a vanishing mass – occurs at a deeply nonperturbative value of the Pauli coupling $\kappa^* = 3.82$, independently of fermion flavor number [18].

To further scrutinize the physical relevance of this continuum theory, we go beyond the Pauli term in the truncation of the effective action. Operators of particular interest are given by dimension-6 four-fermion channels of the Nambu-Jona-Lasinio (NJL) type, which appear in an

arXiv:2403.02907v1 [astro-ph.CO] 5 Mar 2024

The Future of Primordial Black Holes: Open Questions and Roadmap

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March 6, 2024

Abstract

We discuss some of the the open questions and the roadmap in the physics of primordial black holes. Black holes are the only dark matter candidate that is known to actually exit. Their conjectured primordial role is admittedly based on hypothesis rather than fact, most straightforwardly as a simple extension to the standard models of inflation, or even, in homage to quantum physics, more controversially via a slowing-down of Hawking evaporation. Regardless of one's stance on the theoretical basis for their existence, the possibility of primordial black holes playing a novel role in dark matter physics and gravitational wave astronomy opens up a rich astrophysical phenomenology that we lay out in this brief overview.

1 Introduction

Primordial black holes (PBHs) provide an attractive way to resolve the dark matter problem. Unlike essentially all other dark matter particle candidates, BHs actually exist, and there are several robust prospects for determining whether there is a primordial component over a broad mass range. Theoretically PBHs may populate the universe in a humongous range of masses from $10^{-20}\,M_\odot$ to $10^{20}\,M_\odot$. They could be the dark matter for masses around $10^{-12}\,M_\odot$. Moreover even if PBHs are dark matter-subdominant, , they could be responsible for some of the currently observed mergers of BHs in the solar mass range or they may play key roles as rare IMBH (Intermediate Mass BHs in the range $(10^3-10^6)M_\odot$ that may seed both SMBH (Supermassive Black Holes observed in the mass range $(10^6-10^{10})M_\odot$ and massive galaxies in the early universe.

PBHs formed very early and hence may be ubiquitous at the highest redshifts accessible by direct imaging, that is $z \lesssim 100$, when there was little astrophysical competition. This provides us with the possibility of finding truly unique high redshift signatures of PBHs, for example via gravity wave interferometers such as Einstein Telescope and Cosmic Explorer that will probe $z \lesssim 20$, for potential sources of EMRI signals.

Well before these telescopes are in action, there will be 21cm dark ages telescopes destined for the lunar far side, such as LUSEE-Night and DSL to probe PBH accretion imprints on diffuse hydrogen absorption against the CMB to $z \lesssim 100$, both scheduled for deployment in 2026. And on a similar time-scale we anticipate LIGO-class gravity wave telescopes to make significant inroads on the possible existence of solar mass black holes as well as black holes populating the "forbidden" region in the pair

arXiv:2403.02787v1 [nucl-th] 5 Mar 2024

What Can We Learn from Directed Flow at STAR-FTX Energies?

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We present results of simulations of directed flow of various hadrons in Au+Au collisions at collision energies of $\sqrt{s_{NN}} = 3$ and 4.5 GeV. Simulations are performed within the model three-fluid dynamics (3FD) and the event simulator based on it (THESEUS). The results are compared with recent STAR data. The directed flows of various particles provide information on dynamics in various parts and at various stages of the colliding system depending on the particle. However, the information on the equation of state is not always directly accessible because of strong influence of the afterburner stage or insufficient equilibration of the matter. It is found that the crossover scenario gives the best overall description of the data. This crossover EoS is soft in the hadronic phase. The transition into QGP in Au+Au collisions occurs at collision energies between 3 and 4.5 GeV, at baryon densities $n_B \gtrsim 4n_0$ and temperatures ≈ 150 MeV. In-medium effects in the directed flow of (anti)kaons are discussed.

I. INTRODUCTION

The directed flow is one of the most sensitive quantities to the dynamics of nucleus-nucleus collisions and properties of the matter produced in these collisions. It provides information about the stopping power of the nuclear matter, its equation of state (EoS), transition to quark-gluon phase (QGP) and more. All these issues were addressed in the analysis of the STAR data [1] obtained within Beam Energy Scan (BES) program at the Relativistic Heavy-Ion Collider (RHIC). The analysis was performed within various approaches [2–14], which include both hydrodynamic and kinetic models. An important conclusion of these studies is that the transition to the quark-gluon phase is most probably of the crossover or weak-first-order type and it stars at collision energies of $\sqrt{s_{NN}} < 8$ GeV in Au+Au collisions. A promising recent development is prediction of correlation between the directed flow and the angular momentum accumulated in the participant region of colliding nuclei [8, 15–19], which allows a deeper insight into collision dynamics.

The STAR-FXT (fixed-target) data on the directed flow of identified particles at energies $\sqrt{s_{NN}} = 3$ and 4.5 GeV were recently published in Refs. [20, 21]. These data were also analyzed within various, mostly kinetic models [11, 14, 22–33] in relation to various problems: the hyperon production [14, 26, 33], the production of light (hyper)nuclei [30, 31], etc. The EoS of the matter produced in the nucleus-nucleus collisions was the prime topic of the above theoretical considerations. It was discussed mostly in terms of softness and stiffness of the EoS [11, 22–24, 26, 29]. These studies were performed within different transport models: The relativistic version of the quantum molecular dynamics implemented into the transport code JAM [11], the hadronic transport code SMASH [22, 29], the Ultrarelativistic Quantum Molecular Dynamics (UrQMD) [23, 24], and a multiphase transport model [26].

All the aforementioned papers [11, 22–24, 26, 29] reported that stiff (to a different extent) EoS's are preferable for the reproduction of the directed flow (v_1) at $\sqrt{s_{NN}} = 3$ GeV, while the v_1 data at 4.5 GeV require a softer EoS. The latter was interpreted as indication of onset of the phase transition into QGP. This conclusion about preference of the stiff EoS at the energy of 3 GeV appears to contradict the earlier findings. The analysis of KaoS [34] and FOPI [35] data at collision energies $E_{lab} \leq 2A$ GeV ($\sqrt{s_{NN}} \leq 2.7$ GeV) within the Isospin Quantum Molecular Dynamics model led to the conclusion that the soft EoS with the incompressibility $K = 210$ MeV is strongly preferable [35–38]. Although, this energy range is somewhat below of the STAR-FXT one.

The energy range of the BNL Alternating Gradient Synchrontron (AGS), $E_{lab} = 2 - 10.7$ A·GeV ($\sqrt{s_{NN}} =$ 2.7-4.9 GeV), practically coincide with the currently explored STAR-FXT range. The results of the analysis of the AGS data [39, 40] are more controversial. Strong preference of the soft EoS was reported in Refs. [3, 4, 41–43]. In Refs. [3, 4], the EoS additionally softens at $\sqrt{s_{NN}} > 4$ GeV because of onset of the deconfinement transition. However, in Ref. [44] it was found that the best description of the data on the transverse flow is provided by a rather stiff EoS at $2A$·GeV (NL3) while at higher bombarding energies (4–8 A·GeV) a medium EoS ($K = 300$ MeV) leads to better agreement with the data, while the differences in the soft-EoS and stiff-EoS transverse flows become of minor significance at 4–8 A·GeV. In Ref. [45], the proton flow was found to be also independent of stiffness of the EoS, however provided the momentum dependence in the nuclear mean fields is taken into account.

As recent studies [11, 22–26, 29, 32] of the STAR-FXT v_1 data deduced comparatively stiff EoS's at $\sqrt{s_{NN}} = 3$ GeV, some of them predicted comparatively low baryon densities (n_B) for onset of the denfinement transition.

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arXiv:2403.02759v1 [nucl-th] 5 Mar 2024

Kinetic temperature and radial flow velocity estimation using identified hadrons and light (anti-)nuclei produced in relativistic heavy-ion collisions at RHIC and LHC

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(Dated: March 6, 2024)

We report the investigation of the kinetic freeze-out properties of identified hadrons ($\pi^{\pm}$, $K^{\pm}$ and $p(\bar{p})$) along with light (anti-)nuclei $d(\bar{d})$, $t(\bar{t})$ and ^{3}He in relativistic heavy-ion collisions at RHIC and LHC energies. A simultaneous fit is performed with the Blast-Wave (BW) model to the transverse momentum (p_{T}) spectra of identified hadrons together with light (anti-)nuclei produced in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 7.7 – 200 GeV at the RHIC and in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 at the LHC. The energy and centrality dependence of freeze-out parameters, i.e., kinetic freeze-out temperature (T_{kin}) and collective flow velocity $\langle\beta\rangle$ has been studied. It is observed that light (anti-)nuclei also participate in the collective expansion of the medium created in the collision when included in a common fit with the light hadrons. We observe a marginal rise in the T_{kin} and a slight decrease in $\langle\beta\rangle$ when compared to the values obtained from the fit to light hadrons, indicating that heavier particles decouple earlier in time from the fireball compared to the light hadrons due to higher masses and are more sensitive to the effects of the radial flow. A similar $\langle\beta\rangle$ and significant larger T_{kin} is observed when fit is performed to only protons and light (anti-)nuclei. Additionally, we also observe that the T_{kin} increases from central to peripheral collisions, which is consistent with the argument of short-lived fireball in peripheral collisions. Whereas the $\langle\beta\rangle$ shows a decreasing trend from central to peripheral collisions indicating a more rapid expansion in the central collisions. Both, T_{kin} and $\langle\beta\rangle$ show a weak dependence on the collision energy at most energies. We also observe a strong anti-correlation between T_{kin} and $\langle\beta\rangle$.

PACS numbers: 25.75.-q, 25.75.Ld, 25.75.Nq

I. INTRODUCTION

The investigation of the properties of nuclear matter under extreme conditions is one of the main goals of the heavy-ion program at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC) experiments. The ultrarelativistic heavy-ion collisions create a condition suitable for light (anti-)nuclei production, where a significantly high energy density is achieved over a large volume. These conditions produce a very hot and dense matter for a very short interval of time ($\approx 10^{-22}$ seconds) containing approximately equal number of quarks and anti-quarks. This deconfined matter of quarks and gluons, the Quark-Gluon plasma (QGP), is formed during the initial state of collisions. Afterwards, the system experiences a rapid expansion with drop in its temperature and finally undergoes a phase transition towards hadron gas.

In recent years, there has been a significant emphasis on studying the production of light nuclei in heavy-ion collisions at the Bevalac [1], SIS [2, 3], AGS [4–8], SPS [9–13], RHIC [14–21], and LHC [22–27]. The centrality and energy dependence of the production of light (anti-)nuclei has been a topic of significant interest and suggested a relevancy between the critical point and light (anti-)nuclei production [28–32]. However, the precise mechanisms and temporal aspects of light nuclei production in relativistic heavy-ion collisions continue to be subjects of debate due to relatively small binding energies (≈ few MeV) and finite sizes of these nuclei.

It is of significant importance to study the production of light (anti-)nuclei for multiple reasons. First of all, it is not well understood how a cluster is formed in the interior of the fireball during the collision of heavy nuclei, which requires further quantitative investigation. It is probable that a substantial fraction of few-nucleon bound states observed near midrapidity are produced during the latter phases of the reaction, when the hadronic matter experiences dilution and most of the newly formed hydrogen and helium isotopes decouple from the source having no subsequent rescatterings. In this scenario, light (anti-)nuclei may be helpful to probe the dynamics of the fireball at the time of freeze-out.

The evolution of the system produced in relativistic heavy-ion collisions is mainly described by chemical and

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Nuclear medium effects on the properties of $\Lambda(1405)$

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Abstract. We study the $\Lambda(1405)$ resonance with $I(J^P) = 0(1/2^-)$ in the context of the pentaquark hypothesis in nuclear medium. For the investigation of the influence of the nuclear medium on the physical parameters of $\Lambda(1405)$, we propose a molecular-type structure involving K^-p and $\bar{K}^0n$ admixtures, correlated with the nuclear matter density. Our analysis reveals a substantial shift in both mass and residue, approximately 20% and 38%, respectively. These findings have significant implications for experimental researchers aimed at identifying in-medium characteristics of hyperon resonances.

Impact of (magneto-)thermoelectric effect on diffusion of conserved charges in hot and dense hadronic matter

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We investigate the thermoelectric effect, which describes the 5generation of an electric field induced by temperature and conserved charge chemical potential gradients, in the hot and dense hadronic matter created in heavy-ion collisions. Utilizing the Boltzmann kinetic theory within the repulsive mean-field hadron resonance gas model, we evaluate both the diffusion thermopower matrix and diffusion coefficient matrix for the baryon number (B), electric charge (Q), and strangeness (S).The Landau-Lifshitz frame is enforced in the derivation. We find that the thermoelectric effect hinders the diffusion processes of multiple conserved charges, particularly reducing the coupling between electric charge and baryon number (strangeness) in baryon (strangeness) diffusion. Based on the fact that the repulsive mean-field interactions between hadrons have a significant effect on the diffusion thermopower matrix and diffusion coefficient matrix in the baryon-rich region, we extend the investigation to include the impact of the magnetic field, analyzing the magneto-thermoelectric effect on both the diffusion coefficient matrix and the Hall-like diffusion coefficient matrix. The sensitivity of the magnetic field-dependent diffusion thermopower matrix and magneto-thermoelectric modified diffusion coefficient matrix to the choices of various transverse conditions is also studied.

arXiv:2403.02705v1 [nucl-th] 5 Mar 2024

I. INTRODUCTION

Relativistic heavy-ion collision experiments open up a unique portal for understanding the properties of strongly interacting matter under extreme temperatures. A lot of experimental evidence in the relativistic heavy-ion collider (RHIC) [1–4] at Brookhaven National Laboratory (BNL) and in the large hadron collider (LHC) [5–10] at the European Organization for Nuclear Research (CERN) have indicated that a new deconfined state of matter – quark-gluon plasma (QGP) can be created. On the other hand, quantum chromodynamics (QCD) is the fundamental theory of the strong interaction and the lattice QCD calculation has predicted a smooth crossover for QCD matter from a hadronic phase to a QGP phase can be realized with increasing temperature (T) at the small or vanishing baryon chemical potential (μ_B) [11–13]. At large μ_B, the calculations in the low energy QCD effective models, viz., the (Polyakov-loop-) Nambu-Jona-Lasinio model [14–16], the (Polyakov-loop-) quark-meson model [17–20] have indicated that the QCD phase transition becomes a first-order phase transition and terminates at the critical endpoint (CEP) of second-order, which has sparked long-sought debate without conclusive experimental evidence yet [21]. Besides, the Beam Energy Scan (BES) program at RHIC [22, 23] and ongoing experimental programs at Facility for Antiproton and Ion Research (FAIR) [24, 25] and Nuclotron-based Ion Collider fAcility (NICA) [26, 27] also endeavor to shed light on the properties of dense nuclear matter and search the potential signature of the CEP in the QCD phase diagram.

Besides the equilibrium QCD thermodynamic properties, the medium response to perturbation around equilibrium, characterized by transport coefficients, plays an important role in describing the dynamics of bulk matter created in relativistic heavy-ion collisions. The ratio of shear viscosity to entropy density (η/s) has been shown to give a good description of flow data [28–30]. The bulk viscosity to entropy density (ζ/s) exhibits a novel behavior at some characteristic temperatures [31, 32]. During recent research [33, 34], electric conductivity has also been used as an input in magneto-hydrodynamic simulations of heavy-ion collisions. On the other hand, the diffusion coefficient, which describes the medium response to inhomogeneities in the number density and almost is ignored at top RHIC and LHC energies, becomes significant in low-energy heavy-ion collisions. Typically the diffusion coefficient matrix, measuring the coupling among diffusion currents of different conserved charges of the system, is required to give a proper dynamical description of low-energy heavy-ion collisions. This results from the fact that QCD matter constituents (hadrons and quarks) carry multiple quantum conserved numbers, e.g., baryon number (B), electric charge (Q), strangeness (S), etc. The complete diffusion coefficient matrix in both the QGP and hadron gas has been calculated within the Boltzmann kinetic theory [35–37] and the results reveal that the off-diagonal matrix elements in magnitude share

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arXiv:2403.02655v1 [hep-th] 5 Mar 2024

The Mass Gap of the Space-time and its Shape

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Abstract

Snyder's quantum space-time which is Lorentz invariant is investigated. It is found that the quanta of space-time have a positive mass that is interpreted as a positive real mass gap of space-time. This mass gap is related to the minimal length of measurement which is provided by Snyder's algebra. Several reasons to consider the space-time quanta as a 24-cell are discussed. Geometric reasons include its self-duality property and its 24 vertices that may represent the standard model of elementary particles. The 24-cell symmetry group is the Weyl/Coxeter group of the F_4 group which was found recently to generate the gauge group of the standard model. It is found that 24-cell may provide a geometric interpretation of the mass generation, Avogadro number, color confinement, and the flatness of the observable universe. The phenomenology and consistency with measurements is discussed.

"The knowledge at which geometry aims is knowledge of the eternal"— Plato.

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PROCEEDINGS OF SCIENCE

arXiv:2403.02605v1 [nucl-ex] 5 Mar 2024

Double Deeply Virtual Compton Scattering at Jefferson Lab Hall A

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This paper presents our project and perspectives to measure for the first time beam spin asymmetries from Double Deeply Virtual Compton Scattering in the $eP \to e'P'\mu^+\mu^-$ reaction at Jefferson Lab. Our goal is to constrain the so-called Generalized Parton Distribution (GPDs) in a kinematic region that isn't accessible from other reactions, such as Deeply Virtual Compton Scattering, to allow for their extrapolation to "zero skewness", i.e. at a specific kinematic point enabling for tomographic interpretations of the nucleon's partonic structure. We are discussing DDVCS phenomenology and our approach, as well as our experimental project aimed at complementing the SoLID experiment at JLab Hall A with a new muon detector.

25th International Spin Physics Symposium (SPIN 2023)
24-29 September 2023
Durham, NC, USA

*Speaker

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https://pos.sissa.it/

1. Introduction

The so-called Generalized Parton Distribution (GPDs) [1, 2] are matrix elements parametrizing the soft structure of the nucleon in "Hard Exclusive" reactions [3, 4]. GPDs contain information on the longitudinal momentum versus transverse position of the partons (quarks and gluons) [5, 6]. We have been studying GPDs for the last ~30 years as we are looking to move towards multidimensional images of the nucleon structure. One of the interesting interpretations of GPDs is the possibility to access tomographic views of the nucleon, where we can relate the transverse position of the partons to the quark and gluon densities [7]. This kind of interpretation relies on extrapolations of GPDs to certain kinematics that can't be accessed experimentally, and on models, referred to as "zero skewness" [8], i.e. reactions where all the momentum transferred to the nucleon is purely transverse. Our goal is to study Double Deeply Virtual Compton Scattering to constrain the GPDs at this limit.

"Hard Exclusive" reactions refers to: a "hard scale" of at least 1 GeV^2, allowing for factorization between a soft part parametrized by the GPDs, and a hard part, calculable [9]; "exclusivity" refers to all products of the reaction being known, enabling measurement of the total momentum transfer to the nucleon (we use Mandelstam variable "t", the squared momentum transfer). Fig.1 is the general Compton-like process, where a photon is scattered off a quark in the nucleon. We display the factorization lane, the bottom part representing the GPDs. The incoming and scattered photons have to be of different virtuality to allow for a non-zero momentum exchange to the nucleon. We can distinguish between 3 particular cases of "Compton Scattering": Deeply Virtual Compton Scattering (DVCS), where the incoming photon is virtual (spacelike) and the outgoing one is real; Timelike Compton Scattering (TCS), where the incoming photon is real and the outgoing one is virtual, subsequently decaying into a lepton pair; and Double Deeply Virtual Compton Scattering (DDVCS), where both photons are virtual. DVCS has been measured at multiple facilities [10–25], TCS has recently been measured for the first time at JLab [26], DDVCS has never been measured.

There are several GPDs, for quarks and gluons, and to account for relative helicity states of the quark-nucleon system. At leading order and leading twist (lowest order in photon's virtuality related to extra-gluon exchanges), for a spin 1/2 nucleon, we have 4 (x2 for quarks and gluons) chiral-even GPDs, and 4 (x2) chiral-odd GPDs (with quark helicity flip), i.e. 16 total (see for instance [5, 27]). These GPDs depend on 3 variables: t, x (nucleon's longitudinal momentum fraction carried by the parton), ξ ("skewness", related to the longitudinal momentum transfer to the quark in light cone frame). We will neglect here their evolution with the photons' virtuality (namely Q^2=-q^2 and/or Q'^2=q'^2 for incoming and outgoing photons, respectively, defined from their squared 4-momenta). GPDs can't be measured directly: we measure Compton Form Factors (CFFs), functions of the GPDs, accessible from fits of cross sections and asymmetries of the various reactions. Most models are currently constrained by measurements of DVCS only, where GPDs can only be accessed at specific kinematic points, for x=$\pm\xi$. TCS being the "time-reversal" equivalent of DVCS at leading order and leading twist [28], it accesses GPDs at the same kinematics. On the other hand, we can vary the relative virtualities of the two photons in DDVCS to access different kinematics, such as $|x| < \xi$ [5, 29, 30]. It is essential to deconvolute these 2 variables and extrapolate the GPDs to ξ=0 [8], which is needed for tomographic interpretations.

arXiv:2403.02602v1 [nucl-th] 5 Mar 2024

Macroscopic neutrinoless double beta decay: long range quantum coherence

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(Dated: March 6, 2024)

We introduce the concept of "macroscopic neutrinoless double beta decay" (MDBD) for Majorana neutrinos. In this process an antineutrino produced by a nucleus undergoing beta decay, $X \to Y + e^- + \bar{\nu}_e$, is absorbed as a neutrino by another identical X nucleus via the inverse beta decay reaction, $\nu_e + X \to e^- + Y$. The distinct signature of MDBD is that the total kinetic energy of the two electrons equals twice the endpoint energy of single beta decay. The amplitude for MDBD, a coherent sum over the contribution of different mass states of the intermediate neutrinos, reflects quantum coherence over macroscopic distances, and is a new macroscopic quantum effect. We evaluate the rate of MDBD for a macroscopic sample of "X" material, e.g., tritium, acting both as the source and the target. The accidental background for MDBD originating from two separate single beta decays, which contains two final state neutrinos, can be readily rejected by measuring the energy of the detected two electrons. We discuss the similarities and differences between the MDBD and conventional neutrinoless double beta decay.

PACS numbers:

I. INTRODUCTION

The neutrino, if a Majorana rather than a Dirac fermion, would be its own antiparticle. A key experimental signature distinguishing Majorana neutrinos from Dirac neutrinos is nuclear neutrinoless double beta decay (0νDBD),

$$(A, Z) \to (A, Z+2) + e^- + e^-. \tag{1}$$

Despite the importance of determining whether neutrinos are Majorana or Dirac, and despite a major experimental effort, only upper limits for 0νDBD have so far been obtained [1–3]. Ongoing and future experiments with multi-ton detectors will further improve the sensitivity in these searches [4].

The existence of a Majorana neutrino implies lepton-number non-conservation, hence physics beyond the Standard Model. Majorana neutrinos have only two spin states: when massless the left-handed state is a neutrino and the right-handed an antineutrino. The "sea-saw" mechanism for Majorana neutrinos can then provide a natural explanation for the very light neutrino masses inferred from tritium beta decay (TBD) and neutrino oscillation experiments [5].

The standard picture of neutrinoless double beta decay is that the *antineutrino* emitted from a neutron in a nucleus is absorbed as a *neutrino* on a neutron in the same nucleus. But there is in general no requirement in neutrinoless double beta decay that the second neutron be in the same nucleus (or indeed that the second nucleus be the same nuclide as the first, or even that the two down quarks undergoing weak interactions be in different neutrons). In this paper, we introduce the concept of "macroscopic neutrinoless double beta decay" (MDBD), in which a Majorana neutrino emitted from one nucleus is absorbed in a second nucleus. For example, in the single beta decay (XBD) from parent nucleus $X = (A, Z)$ to daughter nucleus $Y = (A, Z+1)$,

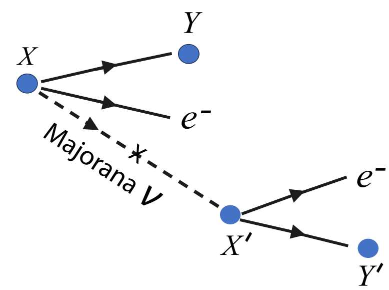

FIG. 1: Illustration of macroscopic neutrinoless double beta decay, with time running to the right. The first nucleus, X undergoes a beta decay emitting an electron and a Majorana antineutrino, which is absorbed as a neutrino by a second nucleus X' in an inverse beta decay. The sum of the energies of the two electron emitted is just the sum of the individual endpoint energies in the beta decays of X and X'.

$$X \to Y + e^- + \bar{\nu}_e, \tag{2}$$

the antineutrino produced is, for Dirac type neutrinos, distinct from ν_e and cannot participate in the inverse beta decay (IXBD) reaction

$$\nu_e + X \to e^- + Y; \tag{3}$$

the nucleus X can only absorb an electron neutrino, ν_e, to reach the final state $e^- + Y$. If neutrinos are Majorana however, then the neutrino and antineutrino are not distinct particles, and the antineutrino in the XBD can then participate in the IXBD. The combination of these

EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Physics Reports

CERN-EP-2024-056
6th March 2024

arXiv:2403.02455v1 [hep-ex] 4 Mar 2024

The quest to discover supersymmetry at the ATLAS experiment

The ATLAS Collaboration

The search for supersymmetry with the ATLAS experiment at the CERN Large Hadron Collider intensified after the discovery of the Higgs boson in 2012. The search programme expanded in both breadth and depth, profiting from the increased integrated luminosity and higher centre-of-mass energy of Run 2, and gaining new sensitivity to unexplored areas of supersymmetry parameter space through the use of new experimental signatures and innovative analysis techniques. This report summarises the supersymmetry searches at ATLAS using up to 140 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV, including the limits set on the production of gluinos, squarks, and electroweakinos for scenarios either with or without R-parity conservation, and including models where some of the supersymmetric particles are long-lived.

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Contents

1 Introduction

One of the most significant contributions of the CERN Large Hadron Collider (LHC) [1] to high-energy physics comes through the particles that the ATLAS [2] and CMS [3] collaborations have *not* found. Both collaborations have pursued an unprecedented programme of searches for phenomena not predicted by the Standard Model (SM). The wide variety of signatures explored, and the richness of the models considered, has had a powerful influence on community's paradigms of physics beyond the Standard Model.

Among these paradigms, supersymmetry (SUSY) [4–9] is one of the most closely examined. The approach of imposing symmetries on Lagrangians led to the construction of electroweak theory, the unification of the weak and electromagnetic interaction and, eventually, the development of the Standard Model. The phenomenology of SUSY stems from requiring the Lagrangian to be invariant under an operator that maps fermionic fields into bosonic ones, and vice versa. It was found that only additional space-time symmetry could be added to the Poincaré group [5]. To impose this symmetry, one needs to add many new *superpartners* of the Standard Model particles. The much richer particle content, and some of the free parameters that one needs to add to make SUSY a broken symmetry (for example, it is known that there is no superpartner of the electron with mass $m = 0.511$ MeV), makes SUSY an ideal framework to accommodate many of the shortcomings of the Standard Model. The quantum corrections to the Higgs boson mass coming from the fermions are counterbalanced by those coming from their superpartners, stabilising the mass to a value near the electroweak scale in a natural way. On top of that, the modified particle content changes the evolution of the running gauge couplings of the SM, potentially allowing

arXiv:2403.02422v1 [hep-ex] 4 Mar 2024

ACE Science Workshop Report

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ABSTRACT

We summarize the Fermilab Accelerator Complex Evolution (ACE) Science Workshop, held on June 14-15, 2023. The workshop presented the strategy for the ACE program in two phases: ACE Main Injector Ramp and Target (MIRT) upgrade and ACE Booster Replacement (BR) upgrade. Four plenary sessions covered the primary experimental physics thrusts: Muon Collider, Neutrinos, Charged Lepton Flavor Violation, and Dark Sectors. Additional physics and technology ideas were presented from the community that could expand or augment the ACE science program. Given the physics framing, a parallel session at the workshop was dedicated to discussing priorities for accelerator R&D. Finally, physics discussion sessions concluded the workshop where experts from the different experimental physics thrusts were brought together to begin understanding the synergies between the different physics drivers and technologies. In December of 2023, the P5 report was released setting the physics priorities for the field in the next decade and beyond, and identified ACE as an important component of the future US accelerator-based program. Given the presentations and discussions at the ACE Science Workshop and the findings of the P5 report, we lay out the topics for study to determine the physics priorities and design goals of the Fermilab ACE project in the near-term.

DESY-24-030

Signatures of ultralight bosons in the orbital eccentricity of binary black holes

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We show that the existence of clouds of ultralight particles surrounding black holes during their cosmological history as members of a binary system can leave a measurable imprint on the distribution of masses and orbital eccentricities observable with future gravitational-wave detectors. Notably, we find that for nonprecessing binaries with chirp masses $\mathcal{M} \lesssim 10\, M_\odot$, formed exclusively in isolation, larger-than-expected values of the eccentricity, i.e. $e \gtrsim 10^{-2}$ at gravitational-wave frequencies $f_{\rm GW} \simeq 10^{-2}$ Hz, would provide tantalizing evidence for a new particle of mass between $[0.5, 2.5] \times 10^{-12}$ eV in nature. The predicted evolution of the eccentricity can also drastically affect the in-band phase evolution and peak frequency. These results constitute unique signatures of boson clouds of ultralight particles in the dynamics of binary black holes, which will be readily accessible with the Laser Interferometer Space Antenna, as well as future mid-band and Deci-hertz detectors.

arXiv:2403.02415v1 [gr-qc] 4 Mar 2024

Introduction. The birth of gravitational-wave (GW) science [1] heralds a new era of discoveries in astrophysics, cosmology, and particle physics [2]. Measuring the properties of GW signals with current and future observatories, such as the Laser Interferometer Space Antenna (LISA) [3], the Einstein Telescope (ET) [4] and Cosmic Explorer (CE) [5], as well as other Mid-band [6] and Deci-hertz detectors [7], not only will unravel the origins of binary black hole (BBH) mergers, it also opens the possibility to discover (very-weakly-coupled) ultralight particles that are ubiquitous in theories of the early universe [8–12]. Notably, the mass, spin alignment, and eccentricity are expected to be correlated with formation channels, *isolated* or *dynamical*, e.g. [13–31]; whereas boson clouds (or "gravitational atoms" [8, 9]), formed around black holes via superradiance instabilities [32–36], can produce a large backreaction on the orbital evolution. Following analogies with atomic physics [37], the cloud may encounter Landau-Zener (LZ) resonances [38], or ionization effects [39–41]. The presence of a cloud then leads to large finite-size effects [37, 42], floating/sinking orbits [38], as well as other sharp features [40], that become unique signatures of ultralight particles in the BBH dynamics.

For the most part, up until now backreaction effects have been studied under the simplified assumption of planar, quasi-circular orbits. The reason is twofold [37]. Firstly, several formation scenarios lead to spins that are parallel to the orbital angular momentum [18]. Secondly, the decay of eccentricity through GW emission in vacuum [43, 44] is expected to have circularized the orbit in the late stages of the BBH dynamics. We retain here the former but relax the latter assumption. As we shall see, adding eccentricity not only introduces a series of *overtones* [41, 45, 46], it can also have a dramatic influence in the orbital dynamics as the cloud transits a LZ-type transition. Although the strength of the new resonances is proportional to the eccentricity, depending on their position and nature (floating or sinking), a small departure from circularity can lead to transitions that not only would deplete the cloud, but also induce a rapid growth of eccentricity towards a large critical (fixed-point) value: $e_{\rm cr} \in [0.3, 0.6]$. As measurements of the eccentricity are correlated with formation channels, the predicted increase can impact the inferred binary's origins. Measurements of larger-than-expected eccentricities would then provide strong evidence for the existence of a new ultralight particle in nature. In particular, because of the critical fixed point, a fraction of the BBHs undergo a rapid growth of orbital eccentricity to a common value. As a result, the distribution of masses and eccentricities may feature a skewed correlation by the time they reach the detector's band. Furthermore, for chirp masses $\mathcal{M} < 10 M_\odot$ and spin(s) aligned with the orbital angular momentum—expected to exclusively form in the field—the presence of a boson cloud at earlier times can shift a fraction of the population towards values of $e \gtrsim 10^{-2}$ at 10^{-2}Hz, readily accessible to LISA [3]. Furthermore, the GW-evolved eccentricity may also be within reach of the planned mid-band [6] or Deci-hertz [7] observatories. For all such events, a new ultralight boson of mass $[0.5, 2.5] \times 10^{-12}$ eV forming a cloud and decaying through a LZ-type transition prior to detection, may be the ultimate culprit.

The more drastic evidence is given when the resonant transition occurs in band with measurable frequency evolution. Plethora of phenomena are discussed in [37, 38] for circular orbits. In addition to overtones, the increase in eccentricity would imply that higher harmonics become more relevant, which in turn affects the peak frequency of the GWs, even for floating orbits. We point out here some salient features and elaborate further on the details elsewhere [46].

The gravitational atom. Ultralight particles of mass μ can form a cloud around a rotating black hole of mass M, via superradiant instabilities [8, 9]. The typical mass of the (initial) cloud scales as $M_{\rm c,0}/M \simeq \alpha$, whereas its typical size is $r_c \simeq \frac{r_g}{\alpha^2}$, with $r_g \equiv \frac{GM}{c^2}$, and

$$\alpha = \frac{GM\mu}{\hbar c} \simeq 0.1 \left(\frac{M}{15 M_\odot}\right) \left(\frac{\mu}{10^{-12}{\rm eV}}\right) . \qquad (1)$$

Draft version March 6, 2024
Typeset using LATEX **twocolumn** style in AASTeX63

arXiv:2403.02398v1 [astro-ph.GA] 4 Mar 2024

Microlensing optical depth and event rate toward the Large Magellanic Cloud based on 20 years of OGLE observations

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(Received; Revised; Accepted)

ABSTRACT

Measurements of the microlensing optical depth and event rate toward the Large Magellanic Cloud (LMC) can be used to probe the distribution and mass function of compact objects in the direction toward that galaxy – in the Milky Way disk, Milky Way dark matter halo, and the LMC itself. The previous measurements, based on small statistical samples of events, found that the optical depth is an order of magnitude smaller than that expected from the entire dark matter halo in the form of compact objects. However, these previous studies were not sensitive to long-duration events with Einstein timescales longer than 2.5–3 years, which are expected from massive ($10 - 100\,M_\odot$) and intermediate-mass ($10^2 - 10^5\,M_\odot$) black holes. Such events would have been missed by the previous studies and would not have been taken into account in calculations of the optical depth. Here, we present the analysis of nearly 20-year-long photometric monitoring of 78.7 million stars in the LMC by the Optical Gravitational Lensing Experiment (OGLE) from 2001 through 2020. We describe the observing setup, the construction of the 20-year OGLE dataset, the methods used for searching for microlensing events in the light curve data, and the calculation of the event detection efficiency. In total, we find 16 microlensing events (thirteen using an automated pipeline and three with manual searches), all of which have timescales shorter than 1 yr. We use a sample of thirteen events to measure the microlensing optical depth toward the LMC $\tau = (0.121 \pm 0.037) \times 10^{-7}$ and the event rate $\Gamma = (0.74 \pm 0.25) \times 10^{-7}\,\mathrm{yr}^{-1}\,\mathrm{star}^{-1}$. These numbers are consistent with lensing by stars in the Milky Way disk and the LMC itself, and demonstrate that massive and intermediate-mass black holes cannot comprise a significant fraction of dark matter.

Keywords: Gravitational microlensing (672), Dark matter (353), Milky Way dark matter halo (1049), Large Magellanic Cloud (903), Primordial black holes (1292), Intermediate-mass black holes (816)

1. INTRODUCTION

The discoveries of gravitational waves produced during mergers of massive black holes in distant galaxies by LIGO and Virgo detectors (Abbott et al. 2016, 2019, 2021, 2023) raised questions if such black holes exist in the Milky Way and, if yes if they can be detected using other means than gravitational waves. Most black holes detected in the Milky Way using electromagnetic observations have typically masses below $15 - 20\,M_\odot$ (Corral-Santana et al. 2016), whereas those detected by gravitational-wave detectors are on average more massive. They can reach more than $100\,M_\odot$ (Abbott et al. 2020a,b).

The origin of black holes discovered by gravitational-wave detectors is a subject of vigorous debate (e.g., Costa et al. 2023 and references therein). Several authors (e.g., Bird et al. 2016; Sasaki et al. 2016;

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arXiv:2403.02397v1 [hep-th] 4 Mar 2024

Physical running of couplings in quadratic gravity

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We argue that the well-known beta functions of quadratic gravity do not correspond to the physical dependence of scattering amplitudes on external momenta, and derive the correct physical beta functions. Asymptotic freedom turns out to be compatible with the absence of tachyons.

Quadratic gravity is an extension of Einstein's theory whose action contains terms quadratic in curvature. In signature $-+++$ it reads

$$S = \int d^4x \sqrt{|g|} \left[\frac{{m_P}^2}{2}(R - 2\Lambda) - \frac{1}{2\lambda} C^2 - \frac{1}{\xi} R^2 \right] , \quad (1)$$

where $m_P = \sqrt{8\pi G}$ is the Planck mass, Λ is the cosmological constant, $C_{\mu\nu\rho\sigma}$ is the Weyl tensor. We will not consider the Euler (Gauss-Bonnet) term here. This theory is renormalizable [1]. In addition to the massless graviton it propagates a massive spin-2 particle that is a ghost and if $\lambda < 0$ it is a tachyon[1]. It also has a massive spin-0 particle that is a tachyon for $\xi > 0$. In spite of these apparent pathologies, it has attracted renewed interest recently [2–8]. In these studies, it is suggested that it may be possible that the ghost state is acceptable, although tachyonic states are considered fatal.

The first attempt to compute beta functions for this theory was made by Julve and Tonin in [9], but that work missed the contribution of the Nakanishi-Lautrup ghosts. This was corrected in [10] and then, with some further corrections, in [11]. The final result is

$$\beta_\lambda = -\frac{1}{(4\pi)^2} \frac{133}{10} \lambda^2 , \quad (2)$$

$$\beta_\xi = -\frac{1}{(4\pi)^2} \frac{5(72\lambda^2 - 36\lambda\xi + \xi^2)}{36} , \quad (3)$$

Since then, these beta functions have been confirmed in several calculations using different techniques [12–16]. With these beta functions, full asymptotic freedom can only be obtained for the case of a tachyonic coupling $\xi > 0$.

The beta functions (2,3) give the dependence of the renormalized λ and ξ on the renormalization scale μ. We call this the *μ-running*. However, what one is really interested in is the dependence of the running couplings on external momenta, that we call *physical running.* [2]

In problems characterized by a single momentum scale p, e.g. the total center of mass energy $p = \sqrt{s}$, the p-dependence is usually the same as the μ-dependence, because for dimensional reasons they occur as $\log(p/\mu)$. In the presence of a non-negligible mass scale m, the amplitude generally contains, in addition to terms of the form $\log(p/\mu)$, also terms of the form $\log(m/\mu)$ and in this way the p-dependence is no longer correctly reflected by the μ-dependence. One clear source of such spurious μ-dependence are tadpoles, Feynman diagrams that by construction do not depend on the external momenta. In such cases, the μ-running is not the same as physical running.

In most familiar quantum field theories such as the Standard Model this is not a problem as one can use mass independent renormalization schemes. However, we claim that it is not always correct in higher derivative theories. Two of us have indeed found that in higher derivative sigma models the scale dependent beta functions calculated with a ultraviolet cutoff [21] or those obtained from the dependence on an infrared cutoff [22] are indeed contaminated by tadpoles, and hence not physical [23]. In the present letter we claim that the same is true in quadratic gravity, and we compute the physical beta functions.

Calculations of the beta functions so far have been based on the background field method, expanding $g_{\mu\nu} = \bar{g}_{\mu\nu} + h_{\mu\nu}$ around a general background $\bar{g}$. In the following a bar always indicates a quantity calculated from

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[1] Ghosts are particles whose propagator is the negative of the usual one, while tachyons are particles with a pole at spacelike momenta.

[2] These and other definitions of running have been discussed in a simple model of a higher-derivative shift-invariant scalar theory, where the full form of the scattering amplitude is accessible [17], see also [18–20].

arXiv:2403.02386v1 [astro-ph.GA] 4 Mar 2024

No massive black holes in the Milky Way halo

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The gravitational wave detectors have unveiled a population of massive black holes that do not resemble those observed in the Milky Way [1–3]. They may have formed due to the evolution of massive low-metallicity stars [4], dynamical interactions in dense stellar environments [5, 6], or density fluctuations in the very early Universe (primordial black holes) [7–9]. If the latter hypothesis is correct, primordial black holes should comprise from several to 100% of dark matter to explain the black hole merger rates observed by gravitational wave detectors [10–12]. If such black holes existed in the Milky Way dark matter halo, they would cause long-timescale gravitational microlensing events lasting years. Here, we present the results of the search for the long-timescale microlensing events among the light curves of 78.7 million stars located in the Large Magellanic Cloud (LMC) that were monitored for 20 years (2001-2020) by the Optical Gravitational Lensing Experiment (OGLE) survey [13]. We did not find any events with timescales longer than one year. The properties of all thirteen microlensing events with timescales shorter than one year detected by OGLE toward the LMC can be explained by astrophysical objects located either in the LMC itself or in the Milky Way disk, without the need to invoke dark matter

in the form of compact objects. We find that compact objects in the mass range from $1.8 \times 10^{-4}\,M_{\odot}$ to $6.3\,M_{\odot}$ cannot compose more than 1% of dark matter, and compact objects in the mass range from $1.3 \times 10^{-5}\,M_{\odot}$ to $860\,M_{\odot}$ cannot make up more than 10% of dark matter. This conclusively rules out primordial black hole mergers as a dominant source of gravitational waves.

Gravitational microlensing was proposed by [14] as a promising tool for searching for dark matter in the Milky Way halo. This idea prompted extensive searches by the first-generation microlensing surveys [15–18]. Here, we analyze the longest digital photometric data set to search for extremely long-timescale microlensing events. The data were collected for nearly 20 years during the third (OGLE-III; 2001–2009; [19]) and fourth (OGLE-IV; 2010–2020; [13]) phases of the OGLE project. Since OGLE-III and OGLE-IV had similar observing setups, it was possible to merge the observations to create a 20-year-long photometric time-series dataset. We developed a new method of reductions of photometric observations, which enabled us to obtain homogeneous light curves. The design of the survey, extraction of photometry, and methods used to search for microlensing events and calculate the event detection efficiency are described in detail in a companion paper [20].

About 33 million objects are detected in the overlapping OGLE-III/OGLE-IV region, and an additional 29 million objects are observed by OGLE-IV only. The number of stars that may be microlensed is even higher because of blending, which occurs when two or more stars cannot be resolved in ground-based seeing-limited images. We used the archival high-resolution images from the Hubble Space Telescope [21] to correct the star counts for blending. After removing the contribution from foreground Milky Way stars, we found that the survey monitored for microlensing about 78.7 million source stars in the LMC brighter than $I = 22$ mag [20].

We searched for microlensing events using a variation of the method described by [22]. The algorithm tries to identify a flat portion of the light curve, and then searches for consecutive data points that are magnified with respect to the flat part. Then, a standard point-source point-lens microlensing model [14] is fitted to the light curve, and the goodness-of-the-fit statistics are evaluated. The events are selected on the basis of a series of selection cuts. This procedure enabled us to find thirteen events that fulfill all detection criteria. Additionally, three events were identified by a manual inspection of the light curves, although they did not meet all selection criteria. The sample of thirteen events is used for a later statistical analysis [20].

We also carried out extensive light curve simulations to measure the event detection efficiency as a function of the event timescale [20]. To this end, we created synthetic light curves of microlensing events by injecting the microlensing signal into the light curves of constant stars observed by the project. Then, we measured the fraction of simulated events that passed all selection criteria. This procedure enabled us to take into account the noise in the data, as well as the effects of irregular sampling, gaps in the data, outliers, etc.

The contribution of primordial black holes (PBHs) and other compact objects to dark matter is often parameterized by $f = \Omega_{\rm PBH}/\Omega_{\rm DM}$, where $\Omega_{\rm PBH}$ is the density of dark matter in the form of PBHs and $\Omega_{\rm DM}$ is the density of dark matter. Note that we expect to detect some gravitational microlensing events even if $f = 0$: they come

arXiv:2403.02000v1 [astro-ph.CO] 4 Mar 2024

Observational Constraints on the Dark Energy with a Quadratic Equation of State

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Abstract

In this study, we introduce a novel late-time effective dark energy model characterized by a quadratic equation of state (EoS) and rigorously examine its observational constraints. Initially, we delve into the background dynamics of this model, tracing the evolution of fluctuations in linear order. Our approach involves substituting the conventional cosmological constant with a dynamically effective dark energy fluid. Leveraging a diverse array of observational datasets encompassing the Planck 2018 Cosmic Microwave Background (CMB), Type Ia Supernovae (SNe), Baryon Acoustic Oscillations (BAO), and a prior on the Hubble constant H_0 (R21), we constrain the model parameters. We establish the model's consistency by comparing the Hubble parameter as a function of redshift against observational Hubble data (OHD), benchmarking its performance against the Standard ΛCDM model. Additionally, our investigation delves into studies of the model's dynamical behavior by computing cosmological parameters such as the deceleration parameter, relative Hubble parameter, and the evolution of the Hubble rate. Furthermore, employing Bayesian analysis, we determine the Bayesian Evidence for our proposed model compared to the reference ΛCDM model. While our analysis unveils the favorable behavior of the model in various observational tests, the well-known cosmological tensions persist when the full dataset combination is explored.

Keywords: Dark Energy, Quadratic Equation of State, Cosmic Voids, Hubble Tension
PACS:

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arXiv:2403.03152v1 [hep-ph] 5 Mar 2024

The Density of Relic Neutrinos Near the Surface of Earth

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(Dated: March 6, 2024)

It has been claimed that matter effects cause an asymmetry in the density of relic neutrinos versus antineutrinos near the surface of Earth, of order $\mathcal{O}(G_F^{1/2}) \sim 10^{-4}$, with the vertical extent $\sim$ 10m. We argue that the effect is of order $\mathcal{O}(G_F) \sim 10^{-8}$, with the vertical extent $\sim$ 1mm.

I. INTRODUCTION

Direct detection of relic neutrinos (cosmic neutrino background) must be just a matter of time – one day it will be achieved and the neutrino density near the surface of Earth will be measured.

An unexpectedly large effect of Earth on the relic Dirac neutrinos was found in [1]. It has been claimed that relic electron neutrinos and μ and τ antineutrinos have an overdensity near the surface of Earth

$$\frac{\delta\rho}{\rho} \sim \frac{\sqrt{m_\nu V}}{T}, \tag{1}$$

where $m_\nu \sim 0.1$eV is the neutrino mass, $T = 1.68 \times 10^{-4}$eV is the temperature that appears in the Fermi-Dirac distribution of cosmic neutrinos $f(k) = 1/(1 + e^{k/T})$, and

$$V \sim G_F \frac{\rho_E}{m_p} \tag{2}$$

is the neutrino potential inside Earth; ρ_E is the mass density near the surface of Earth. According to [1] this $O(G_F^{1/2}) \sim 10^{-4}$ overdensity has the vertical extent of $\sim$ 10m.

We will show that in fact there is an *underdensity*, of order $O(G_F) \sim 10^{-8}$, with the vertical extent $\sim$ 1mm, if one follows [1] and treats different neutrino flavors as independent non-relativistic particles.

A more realistic approach would be to work with a 3×3 non-diagonal potential in the neutrino mass basis. But since this does not change the qualitative conclusion, we stick to a simple toy model with only electron neutrinos, within which the precise value of density contrast is derived in §III: at the surface of a large sphere, with uniform density ρ_E and constant atomic and mass numbers Z,A inside,

$$\frac{\delta\rho}{\rho} = \mp \frac{\ln 2}{3\zeta(3)} \frac{m_\nu V_0}{T^2}, \tag{3}$$

where upper (lower) sign refers to neutrinos (antineutrinos), and [2]

$$V_0 = \frac{3\frac{Z}{A} - 1}{2\sqrt{2}} G_F \frac{\rho_E}{m_p} \tag{4}$$

giving

$$\frac{\delta\rho}{\rho}|_{\rm water} = \mp \frac{\sqrt{2}\ln 2}{18\zeta(3)} \frac{m_\nu}{m_p} \frac{G_F \rho_{\rm water}}{T^2} = \mp 8.5 \times 10^{-9} \times \frac{m_\nu}{0.1{\rm eV}}. \tag{5}$$

The paper is organized as follows:

- In §II we prove a "Density Theorem" for Maxwell-Boltzmann particles, showing that for a potential barrier there is an $\mathcal{O}(G_F)$ underdensity. We then prove that for Fermi-Dirac, there is also an *underdensity.*
- In §III we apply the thermal method of §II to the Earth potential to calculate the neutrino and antineutrino density at order $\mathcal{O}(G_F)$, obtaining Eq.(3).
- In §IV we show that the first-order perturbation theory agrees with the thermal method.
- In §V we discuss the flat-Earth approximation. It, too, agrees with the thermal method.
- In §VI we list the sources of discrepancy between [1] and our conclusion.

II. THE "DENSITY THEOREM"

In thermal equilibrium, the density of a non-relativistic classical gas in a potential $V(\mathbf{r})$ is given by $n(\mathbf{r}) = n_0 \exp(-V(\mathbf{r})/T)$ assuming the potential vanishes at infinity, where the gas density is n_0. For a *collisionless* gas with Maxwell-Boltzmann distribution at infinity, we still have $n(\mathbf{r}) = n_0 \exp(-V(\mathbf{r})/T)$, as long as the potential energy is positive and has no local minima. This is because in such potentials all trajectories come from infinity and the equilibrium distribution function depends only on the particle energy [3].

By the same argument collisionless, non-degenerate quantum particles with Maxwell-Boltzmann distribution

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arXiv:2403.03128v1 [hep-ph] 5 Mar 2024

Probing Recoil Signatures of Inelastic Dark Matter

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Abstract

Different dark matter (DM) candidates could have different types of DM-lepton and/or DM-quark interactions. For direct detection experiments, this leads to diversity in the recoil spectra, where both DM-electron and DM-nucleus scatterings may contribute. Furthermore, kinematic effects such as those of the inelastic scattering can also play an important role in shaping the recoil spectra. In this work, we systematically study signatures of the light exothermic inelastic DM from the recoil spectra including both the DM-electron scattering and Migdal effect. Such inelastic DM has mass around (sub-)GeV scale and the DM mass-splitting ranges from 1 keV to 30 keV. We analyze the direct detection sensitivities to such light inelastic DM. For different inelastic DM masses and mass-splittings, we find that the DM-electron recoil and Migdal effect can contribute significantly and differently to the direct detection signatures. Hence, it is important to perform combined analysis to include both the DM-electron recoil and Migdal effect. We further demonstrate that this analysis has strong impacts on the cosmological and laboratory bounds for the inelastic DM.

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Prepared for submission to JHEP

TTP24-004, P3H-24-014

arXiv:2403.03078v1 [hep-ph] 5 Mar 2024

N-jettiness soft function at next-to-next-to-leading order in perturbative QCD

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Abstract: We derive a compact representation of the *renormalized* N-jettiness soft function that is free of infrared and collinear divergences through next-to-next-to-leading order in perturbative QCD. The number of hard partons N is a parameter in the formula for the finite remainder. Cancellation of all infrared and collinear singularities between the bare soft function and its renormalization matrix in color space is demonstrated analytically.

arXiv:2403.03001v1 [hep-ph] 5 Mar 2024

Higgs couplings in SMEFT via Zh production at the HL-LHC

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Abstract: We study the Higgs couplings present in the Zh associated production mode at the Large Hadron Collider (LHC) in presence of both CP even and CP odd dimension 6 Standard Model Effective Theory (SMEFT) operators. The analysis is performed mainly in context of the HL-LHC (with $\sqrt{s}$ =14 TeV and luminosity 3000 fb^{-1}) setup using cut based as well as machine learning techniques. The analysis shows significant betterment in the signal significance by using the machine learning technique. We also do a χ^2 analysis, which reveals a significant change in the sensitivity of the coupling modifiers due to the presence of effective operators, in particular due to the four point $qqZh$ interaction. The presence of dimension six CP odd four point operators, which contributes at $\mathcal{O}(\Lambda^{-4})$ order due to lack of interference with the SM contributions, can only have sensitivity with smaller NP scale at the HL-LHC, after addressing the effective limit and constraints.

Keywords: Higgs production, Higgs properties, SMEFT

arXiv:2403.02916v1 [hep-ph] 5 Mar 2024

Microscopic parametrization of the near threshold oscillations of the nucleon time-like effective electromagnetic form factors

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We present an analysis of the recent near threshold BESIII data for the nucleon time-like effective form factors. The damped oscillation emerging from the subtraction of the dipole formula is treated in non-perturbative-QCD, making use of the light cone distribution amplitudes expansion. Non-perturbative effects are accounted for by considering Q^2-dependent coefficients in such expansions, whose free parameters are determined by fitting to the proton and neutron data. Possible implications and future analysis have been discussed.

I. INTRODUCTION

The theoretical impossibility of describing the nucleon internal structure in terms of strongly interacting quarks and gluons, which are the fundamental fields of quantum chromodynamics, enhances the electromagnetic form factors (EMFFs) to the role of unique and privileged tools to unravel the dynamics underlying the electromagnetic interaction of nucleons. They provide the most effective description of the mechanisms that determine and rule the dynamic and static properties of nucleons. In specific reference frames, EMFFs represent the Fourier transforms of spatial charge and magnetic momentum densities.

Recently, the BESIII [1] experiment measured the time-like nucleon form factors (FFs) at center-of-mass energies between 2.0 GeV and 3.5 GeV [2–6]. These data present an oscillating behavior [7–12], which manifests itself as a periodic, exponentially dumped component over the typical dipolar carrier, usually identified as the only contribution. The nature of such an oscillating component is still unknown. Possible explanations rely either on the final state interaction between the baryon and the antibaryon, or in a phenomenon intrinsic to the baryon structure. In the latter case, the invoked phenomenon would be encoded by the EMFFs of nucleons.

In order to investigate this eventuality we propose a parametrization for the EMFFs defined by considering the nucleons as triplets of collinear quarks lying at light-like distances in the light-front framework [13].

The matrix element of the "+" component of the hadronic current J^μ, which depends directly on the EMFFs, evaluated between the baryon and antibaryon particle states, can then be expanded using the Lorentz invariance of the three quark Fock state's matrix elements.

The resulting form depends on a set of functions of the four momentum squared fractions, called light cone distribution amplitudes (LCDAs), and a deep knowledge of their expression can provide further information about the form factors shape. Using the $\mathcal{L}_{\rm QCD}$ conformal symmetry [14], the LCDAs are expanded on a polynomial basis, the most common choice being represented by the orthonormal Appell polynomials, defined on the triangle $T(x_1, x_3) = \{(x_1, x_3) \in \mathbb{R} : x_1 > 0, x_3 > 0, x_1 + x_3 < 1\}$, where $x_i = k_i^+/P^+$ are the quark's light front momentum fractions along is the $(^+)$ direction and so the following relation holds: $\sum_{i=1}^3 x_i = 1$. The only unknown quantities now are the expansion coefficients, which have to be determined considering the phenomenology of the problem. The nonperturbative coefficients admit an evolution equation in the conformal symmetry framework, and their values can be determined theoretically by QCD sum rules. On the other hand, we are considering a center of mass energy of the system between 2.0 GeV and 3.5 GeV, so we are not allowed to use perturbative methods. What we propose then is to perform a truncated Laurent expansion of the non-perturbative coefficients over the negative powers of the four momentum squared, subsequently performing a fit over the recent BESIII experimental data to determine these coefficients. The final goal of this description is to find whether the oscillations of the EMFFs can be described by the model functions.

II. THE MICROSCOPIC MODEL

One of the most effective ways to describe subnuclear processes is to work on a light front framework, expanding the involved particle states in a free particle state basis, commonly known as Fock states. For a baryon we

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arXiv:2403.02897v1 [hep-ph] 5 Mar 2024

Rare B and K decays in a scotogenic model

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(Dated: March 6, 2024)

Abstract

A scotogenic model can radiatively generate the observed neutrino mass, provide a dark matter candidate, and lead to rare lepton flavor-violating processes. We aim to extend the model to establish a potential connection to the quark flavor-related processes within the framework of scotogenesis, enhancing the unexpectedly large branching ratio (BR) of $B^+ \to K^+\nu\bar{\nu}$, observed by Belle II Collaboration. Meanwhile, the model can address tensions between some experimental measurements and standard model (SM) predictions in flavor physics, such as the muon $g-2$ excess and the higher BR of $B_s \to \mu^-\mu^+$. We introduce in the model the following dark particles: a neutral singlet Dirac-type lepton (N); two inert Higgs doublets ($\eta_{1,2}$), with one of which carrying a lepton number; a charged singlet dark scalar (χ^+), and a singlet vector-like up-type dark quark (T). The first two entities are responsible for the radiative neutrino mass, and χ^+ couples to right-handed quarks and leptons and can resolve the tensions existing in muon $g-2$ and $B_s \to \mu^-\mu^+$. Furthermore, the BR of $B^+ \to K^+\nu\bar{\nu}$ can be enhanced up to a factor of 2 compared to the SM prediction through the mediations of the dark T and the charged scalars. In addition, we also study the impacts on the $K \to \pi\nu\bar{\nu}$ decays.

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arXiv:2403.02859v1 [hep-ph] 5 Mar 2024

On instabilities of perturbations in some homogeneous color-electric and -magnetic backgrounds in $SU(2)$ gauge theory.

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(Dated: March 2024)

We consider the instabilities of field perturbations around a homogeneous background color-electric and/or -magnetic field in SU(2) pure gauge theory. We investigate a number of distinct cases of background magnetic and electric fields, and compute the dispersion relations in the linearised theory, identifying stable and unstable momentum modes. In the case of a net homogenous non-abelian B-field, we compute the non-linear (quadratic and cubic) corrections to the equation of motion, and quantify to what extent the instabilities are tempered by these non-linearities.

I. INTRODUCTION

The thermalisation process of non-abelian gauge fields has been the subject of intense study, in particular in the context of heavy ion collisions (HIC) (see [1] for a comprehensive review). In the initial stages of the collision, anisotropic particle distributions along and perpendicular to the beam line may create large anisotropic classical fields [2–6]. In this background, which is not necessarily homogeneous, perturbations may under certain conditions grow (semi-)exponentially. These (plasma) instabilities may result in long-wavelength fluctuations with very large occupation numbers, that may impact the equilibration process as well [1, 7–9]. It turns out that fast hydrodynamization may likely be understood from kinetic theory with input from perturbation theory [10–18], but a thorough understanding of also the non-perturbative dynamics is still of great interest.

Instabilities in anisotropic backgrounds are well-known from both abelian and non-abelian gauge theory [19]. While a U(1) theory produces linear field equations of motion for the gauge field instabilities, which could then in principle grow very large, for QCD the equations of motion are non-linear and the instabilities could turn out to be short-lived and irrelevant. The abelianization phenomenon [20] implies that there will may be directions in field space, where non-linear contributions vanish, and where the instability could continue unhindered for some time. Ultimately, this will depend on the relative magnitude of the non-linearities, the range of modes that become unstable and the self-coupling. Substantial work has been performed analytically and numerically on plasma instabilities in QCD and QCD-like theories (see for instance [21–25]), both in a HIC context and for simplified models.

In the present work we will explore the instabilities of gauge field perturbations around homogeneous and constant E and B fields in pure classical SU(2) gauge theory. For simplicity, we will ignore any fermions coupled to the gauge fields, which may feel and enhance the anisotropy. Our approach is inspired by [26, 27], where the authors investigated the dispersion relations of perturbations in the linearized theory, in a variety of gauge field backgrounds. Part of the present work is an extension of their analysis, while later parts attempts to go beyond the linear approximation.

A. The equations of motion order by order

The classical equation of motion for pure SU(2) gauge theory reads

$$D_\mu^{ab} F^{\mu\nu,b} = j^{\nu,a}, \tag{1}$$

where the covariant derivative is

$$D_\mu^{ab} = \partial_\mu \delta^{ab} - g\epsilon^{abc} A_\mu^c, \tag{2}$$

and the field strength tensor is

$$F^{\mu\nu,a} = \partial^\mu A^{\nu,a} - \partial^\nu A^{\mu,a} + g\epsilon^{abc} A^{\mu,b} A^{\nu,c}. \tag{3}$$

The gauge field $A_{\mu,a}$ is a 12-component vector, corresponding to colour indices $a = 1, 2, 3$ and Lorentz indices $\mu = 0, 1, 2, 3$. Because of gauge invariance, there is some redundancy in these degrees of freedom, and we will make use of this point shortly. The metric signature is taken to be $(+ - --)$, so that $x_0 = x^0 = t$ and $-x_i = x^i = (x, y, z)$, and $\partial^0 = \partial_0 = \partial/\partial t$, $-\partial^i = \partial_i = \partial/\partial x^i$. Then $E^{i,a} = F^{i0,a}$, while $B^{i,a} = \frac{1}{2}\epsilon^{ijk} F^{kj,a}$.

We will assume that the gauge field may be decomposed into a background field and a fluctuation, with the notation

$$A_a^\mu(x,t) = \bar{A}_a^\mu(x,t) + h_a^\mu(x,t), \tag{4}$$

and with an assumption that the fluctuations are in some sense "small", $h_a^\mu \ll \bar{A}_a^\mu$. It then makes sense to expand order by order in h_a^μ.

Background field

The equation of motion for the background field (expanding to zero'th order in the fluctuation h_a^μ) is simply

$$\bar{D}_\mu^{ab} \bar{F}^{\mu\nu,b} = j^{\nu,a}, \tag{5}$$

where the bar on $\bar{D}_\mu^{ab}$ and $\bar{F}^{\mu\nu,b}$ indicate that they are expressed only in terms of the background field $\bar{A}$. We have

arXiv:2403.02731v1 [hep-ph] 5 Mar 2024

NITEP 202

Attempt Constructing a Model of Grand Gauge-Higgs Unification with Family Unification

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Abstract

We discuss a possibility whether a model of grand gauge-Higgs unification incorporating family unification in higher dimensions can be constructed. We first extend a five dimensional $SU(6)$ grand gauge-Higgs unification model to a five dimensional $SU(7)$ grand gauge-Higgs unification model compactified on an orbifold S^1/Z_2 to obtain three generations of quarks and leptons after symmetry breaking of the larger family unified gauge group. A prescription of constructing a six dimensional $SU(N)$ grand gauge-Higgs unification model including a five dimensional $SU(7)$ grand gauge-Higgs unification after compactifying the sixth dimension on an orbifold S^1/Z_2 is given. We find a six dimensional $SU(14)$ grand gauge-Higgs unification model with a set of representations containing three generations of quarks and leptons.

Light Thermal Dark Matter Beyond p-Wave Annihilation in Minimal Higgs Portal Model

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(Dated: March 6, 2024)

arXiv:2403.02721v1 [hep-ph] 5 Mar 2024

Abstract

This study explores a minimal renormalizable dark matter (DM) model, incorporating a sub-GeV Majorana DM and a singlet scalar particle ϕ. Using scalar and pseudo-scalar interactions (couplings c_s and c_p), we investigate implications for DM detection, considering s-wave, p-wave, and combined (s+p wave) contributions in DM annihilation cross-section, as well as loop-correction contributions to DM-nucleon elastic scattering. Identifying a broad parameter space ($10\,\mathrm{MeV} < m_\chi \lesssim m_\phi$) within the 2σ allowed region, we explore scenarios ($|c_s| \gg |c_p|$, $|c_s| \ll |c_p|$, and $|c_s| \approx |c_p|$). We find that (i) a non-zero pseudo-scalar coupling alleviates direct detection constraints as a comparison with the previous pure scalar coupling case; (ii) CMB observations set stringent limits on pseudo-scalar interaction dominant cases, making s-wave annihilation viable only for $m_\chi > 1\,\mathrm{GeV}$; (iii) the preferred ϕ-resonance region can be tested in the future indirect detection experiments, such as e-ASTROGAM.

Limits on scalar dark matter interactions from radiative corrections

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There is limited information about interaction strength of scalar dark matter candidate with hadrons and leptons for scalar particle mass exceeding 10^{-3} eV while its interaction with photon is well-studied. The scalar-photon coupling constant receives quantum corrections from one-loop Feynman diagrams which involve the scalar-lepton, scalar-quark and scalar-W boson vertices. We calculate these one-loop quantum corrections and find new limits on the scalar particle interactions with electron, muon, tau, quarks, nucleons, gluons and W boson for $m_\phi < 15$ MeV by re-purposing the results of experiments measuring the scalar-photon interaction. Limits on interactions with heavy leptons and quarks have been obtained for the first time, limits on other interactions in certain mass intervals are 2 to 15 orders of magnitude stronger than those presented in previous publications.

arXiv:2403.02685v1 [hep-ph] 5 Mar 2024

I. INTRODUCTION

Scalar and pseudoscalar fields are very promising candidates for dark matter (DM) particles. The pseudoscalar DM candidates are exemplified by the QCD axion which represents a consistent extension of the Standard Model and helps resolving the strong CP problem (see, e.g., [1] for a review). The CP-even counterpart of the axion field is a dilaton ϕ [2], which is strongly motivated by superstring theory, see, e.g., Refs. [3–8]. Scalar field DM candidates appear also in chameleon models of gravity, see, e.g., Ref. [9].

Since the preferred interaction channel between the scalar field and the visible matter particles is not known, it is generally assumed that all types of interactions are allowed, and the strengths of these interactions should be measured experimentally. The leading interaction vertices should be linear with respect to the scalar field, although quadratic interactions are also of interest, see, e.g., Refs. [10–12]. Therefore, the majority of experiments searching for the scalar DM candidates focus on measurements of coupling constants of this scalar field to photon, $g_{\phi\gamma}$ and electron $g_{\phi e}$. The results of these measurements are summarized in Refs. [13, 14]. The channel of hadronic interactions of this scalar field remains less studied.

This paper is devoted to the study of interaction of the scalar field with leptons, quarks and W boson. We show that it is possible to re-purpose the results of the experiments measuring the scalar-photon interaction constant for obtaining new limits on strength of interaction of the scalar field with leptons, quarks and W boson. The main idea is that the scalar-photon coupling constant $g_{\phi\gamma}$ receives quantum corrections from one-loop Feynman diagrams involving the scalar-fermion and scalar-W boson vertices. In other words, the scalar field can decay into two photons via fermionic and W boson loops. Thus, using the relation between the scalar-photon and scalar-fermion or scalar-W interaction constants allows us to find new constraints on the scalar-lepton, scalar-quark and scalar-W boson interactions.

In the next section, we present the general expression for quantum corrections to the scalar-photon interaction constant from one-loop Feynman graphs. This process is analogous to the decay of the Higgs field into two photons mediated by quarks, leptons or W bosons calculated in Refs. [15, 16]. In Sec. II we apply the one-loop relation between the coupling constants for obtaining new limits on the interaction of the scalar DM candidate with leptons, quarks, nucleons, W boson and gluons. A short summary of the results is given in the last section.

In this paper, we use natural units with $\hbar = c = 1$.

II. ONE-LOOP CONTRIBUTION TO SCALAR-PHOTON COUPLING

Let ϕ be a real scalar field representing DM particles with mass m_ϕ. In the model of dilaton-like DM [11, 12, 17, 18], this field may have the following interaction vertices to the photon field with Maxwell field strength $F_{\mu\nu}$, to quarks or leptons described by Dirac fermions f, ($f = e, \mu, \tau, u, d, s, c, b, t$ for electron, muon, tau, up, down, strange, charm, bottom and top quarks, respectively), to gluons $G^a_{\mu\nu}$ and to $W^\pm_\mu$ bosons

$$\mathcal{L}_{\rm int} = \frac{1}{4} g_{\phi\gamma}\phi F^{\mu\nu}F_{\mu\nu} - \sum_f g_{\phi f}\phi \bar{f} f + \frac{1}{4} g_{\phi g}\phi G^{\mu\nu a}G^a_{\mu\nu} + g_{\phi W} m_W \phi W^{+\mu}W^-_\mu \,. \tag{1}$$

The coupling constant $g_{\phi\gamma}$ receives quantum corrections from fermionic loop diagrams with the scalar-fermion interaction quantified by the coupling constant $g_{\phi f}$ and from W-boson loop involving the vertex with $g_{\phi W}$ coupling. The leading contributions are represented by the triangle Feynman graphs in Fig. 1. The corresponding

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arXiv:2403.02551v1 [hep-ph] 5 Mar 2024

Femtoscopy analysis of ultra-soft pion trap at LHC energies

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(Dated: March 6, 2024)

Femtoscopy studies of pion radiation in heavy-ion collisions have been conducted extensively at all available collider energies, both theoretically and experimentally. In all these studies a special interest is given to m_T dependency of pion femtoscopy radii, usually approximated by a power-law function at transverse momenta above 200 MeV/c. However, the radii behaviour has been much less explored for the ultra-soft pions, possessing the transverse momentum comparable to or lower than the pion mass. For many experimental setups this region is difficult to measure. In this work we present theoretical calculations of pion emission in the ultra-soft region in the two hybrid models — iHKM and LHYQUID+THERMINATOR2. Along with the particle transverse momentum spectra, we present the calculated femtoscopy radii, both in one-dimensional and three-dimensional representations. We investigate the radii dependence on pair m_T and observe, in particular, a departure from the power-law behaviour at ultra-soft momenta, potentially reflecting a decoupling of such slow pions from the rest of collectively expanding system. We provide the theoretical interpretation of this result and discuss its significance, in particular, for the ongoing non-identical particle femtoscopy analysis for pairs consisting of a pion and a baryon (or of a pion and a charmed meson).

I. INTRODUCTION

The interferometry of particles emitted from the small radiating source enables one to study the evolving geometry of that source. The particle interferometry has originated from the experimental paper [1] and theoretical works [2, 3]. In the latter it was also found that the results for the quantum statistics correlation effect for two close sources of identical particle emission in collision physics are formally similar to those for classical intensity correlations of the light radiation coming from different parts of the star, known in astronomy as the Hanbury Brown – Twiss (HBT) effect [4–6]. The similarity, as well as the difference between the quantum correlations in identical-particle pairs and the classical HBT effect are analyzed, e.g., in [7]. Note, that the correlation femtoscopy method, initially developed for finding the overall *size* of identical quantum particles' source, now is considered to measure the *homogeneity lengths* [8] of such femto-small sources. This general interpretation is especially important for the studies of the space-time structure of expanding sources, such as those created in proton/antiproton and heavy-ion collisions [1–3, 9–14].

The homogeneity lengths, defined as a result of correlation femtoscopy analysis, reflect the spatial dimensions of the region within the entire strongly interacting system formed in the collision, from which particles are emitted with similar velocities (having close, nearly coinciding values and directions) [8, 15]. Gaussian parameterization for the particle emission source function (SF) and the two-particle correlation function (CF) are usually used in femtoscopy studies, although the realistic source shape differs from a perfect Gaussian — e.g., resonance decay contributions cause the exponential behaviour near the peak of the correlation function. The conventional use of the Gaussian shape allows one to standardize the description of experimental data and easily compare the results of different femtoscopy measurements, as well as to interpret the obtained radii as the homogeneity lengths. It is also well-motivated experimentally in heavy-ion collisions, where correlation shapes for pions in 3D analyses are universally observed to be Gaussian in a wide range of centralities and pair transverse momenta. The study of the dependence of the radii on the particle species, collision type and collision energy is the main objective of the femtoscopic analysis of heavy-ion collisions.

In experimental studies, one clearly observes certain types of universal scaling behaviour for the measured femtoscopy scales. For a given colliding system and collision energy a linear scaling of the femtoscopic radii is universally observed versus cube root of the final state mean particle multiplicity $\langle dN_{ch}/d\eta\rangle^{1/3}$ [16–22]. A similar scaling across collision energies and colliding systems is only approximate [23, 24]. The radii versus the pair transverse momentum exhibit a power-law-like scaling in pair transverse mass m_T ($m_T = \sqrt{k_T^2 + m^2}$, where k_T is pair mean transverse momentum, $k_T = |\mathbf{p}_{T1} + \mathbf{p}_{T2}|/2$, and m is particle mass) [16, 17, 25–30]. In heavy-ion collisions both these scalings are predicted by hydrodynamic models [31]. Specifically, the m_T scaling is explained as a direct consequence and one of the main signatures of the collective radial flow of the system.

The observed m_T power-law scaling means a decrease of the radii with growing m_T that is a signature of hydrodynamic collectivity, typical for all particle species affected by the same flow field. Such dependence can be helpful for the prediction of the source size at certain m_T through the interpolation between radii measured at different m_T values. Nonetheless, the m_T range of experimental radii measurement depends on the acceptance of the detectors used in the study, and the very-low-m_T region has not been reached yet via such measurements.

arXiv:2403.02538v1 [hep-ph] 4 Mar 2024

Thermal effects on sound velocity peak and conformality in isospin QCD

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(Dated: March 6, 2024)

We study thermal effects on equations of state (EOS) in isospin QCD, utilizing a quark-meson model coupled to a Polyakov loop. The quark-meson model is analyzed at one-loop that is the minimal order to include quark substructure constraints on pions which condense at finite isospin density. In the previous study we showed that the quark-meson model at zero temperature produces the sound velocity peak and the negative trace anomaly in the domain between the chiral effective theory regime at low density and the perturbative QCD regime at high density, in reasonable agreement with lattice simulations. We now include thermal effects from quarks in the Polyakov loop background and examine EOS, especially the sound velocity and trace anomaly along isentropic trajectories. At large isospin density, there are three temperature windows; (i) the pion condensed region with almost vanishing Polyakov loops, (ii) the pion condensed region with finite Polyakov loops, and (iii) the quark gas without pion condensates. In the domain (i), the gap associated with the pion condensate strongly quenches thermal excitations. As the system approaches the domain (ii), thermal quarks, which behave as non-relativistic particles, add energy density but little pressure, substantially reducing the sound velocity to the value less than the conformal value while increasing the trace anomaly toward the positive value. Approaching the domain (iii), thermal quarks become more relativistic as pion condensates melt, increasing sound velocity toward the conformal limit. Corrections from thermal pions are also briefly discussed.

I. INTRODUCTION

Recent observations for two-solar mass neutron stars (NSs) [1–6] and the inferred radii of $\sim$ 12-13 km [7–10], together with the low density nuclear constraints [11–13], imply that the equation of state (EOS) in QCD exhibits rapid soft-to-stiff evolution [14], i.e., the pressure grows rapidly as density increases. A useful measure for the evolution of stiffness is (adiabatic) sound velocity $c_s = (\partial P/\partial \varepsilon)^{1/2}$ where the derivative is taken for a fixed entropy. In the dilute regime, nuclear theories predict small c_s^2 of ~ 0.1 at baryon density $n_B \simeq n_0$ [11] ($n_0 \simeq 0.16\,\mathrm{fm}^{-3}$: nuclear saturation density), while in the high density limit c_s^2 approaches $1/3$. In the intermediate regime, there is a domain where c_s^2 makes a peak whose height exceeding $1/3$. In addition, recently the trace anomaly [15], $\Delta_{\rm tr} = 1/3 - P/\varepsilon$, attracts attention which contains information about the absolute value of P, in addition to the slope, at a given ε. The vanishing of the trace anomaly implies the system being in the conformal limit. The sound velocity peak and trace anomaly are the key quantities to infer the relevant degrees of freedom, quarks or hadrons or else, and hence have crucial importance to characterize the state of matter.

To test theoretical conceptions in dense QCD, it is useful to study QCD-like theories such as two-color or isospin QCD [16–18], for which lattice simulations are doable without suffering from the sign problem. For example, lattice simulations for two-color QCD [19, 20] have demonstrated the existence of the sound velocity peak, and subsequently other simulations in isospin QCD also have confirmed it [21, 22].

In a recent work [23], we have analyzed a quark-meson model for isospin QCD which should be suitable for the regime intermediate between hadronic and weakly coupled quark matter. More precisely, a dense matter starts with the Bose-Einstein-Condensation (BEC) phase of pions and smoothly changes into the Bardeen-Cooper-Schrieffer (BCS) phase with the pion condensates on top of the quark Fermi sea. This can be regarded as the hadron-to-quark crossover in which the condensates (order parameters) have the same quantum number but the qualitative features change. We delineated the microphysics relevant to the sound velocity peak and trace anomaly. Respecting the symmetry, the model results at low density are in good agreement with those from the Chiral effective field theory (ChEFT) [24–26] and lattice simulations [21, 22]. In the transient regime from hadronic to quark matter, we found that the sound velocity peak is developed and remains larger than $1/3$ until the density reaches the pQCD domain, $\mu_I \sim 1$ GeV. One of possible explanations for such slow reduction of c_s^2 is non-perturbative power corrections of $\sim +\Lambda_{\rm QCD}^2 \mu_I^2$ to the pressure, where the BCS gap of $\Delta \sim$ 200-300 MeV appears in place of $\Lambda_{\rm QCD}$ [23]. The power corrections add negative contributions to the trace anomaly, and hence the trace anomaly may be usable as a measure of non-

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Electroweak metastability and Higgs inflation

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arXiv:2403.02461v1 [hep-ph] 4 Mar 2024

Abstract

Extrapolating the Standard Model Higgs potential at high energies, we study the barrier between the electroweak and Planck scale minima. The barrier arises by taking the central values of the relevant experimental inputs, that is the strong coupling constant and the top quark and Higgs masses. We then extend the Standard Model by including a non-minimal coupling to gravity, and explore the phenomenology of the Higgs inflation model. We point out that even configurations that would be metastable in the Standard Model, become viable for inflation if the non-minimal coupling is large enough to flatten the Higgs potential at field values below the barrier; we find that the required value of the non-minimal coupling is smaller than the one needed for the conventional Higgs inflation scenario (which relies on a stable Standard Model Higgs potential, without any barrier); in addition, values of the top mass which are slightly larger than those required in the conventional scenario are allowed.

1 Introduction

In the pure Standard Model (SM), and depending on the value of the electroweak parameters, there is the possibility of having a second minimum at high energies [1–3]. As it is well known, the experimental data suggest that the electroweak vacuum is likely to be metastable rather than stable [4–7], although it will be difficult to exclude stability in future [8, 9]. The study of the shape of the Higgs effective potential at high energy is a relevant issue, also in view of the possible role of the Higgs field as the inflaton; for this sake, a region where the Higgs potential becomes sufficiently flat, for large enough values of the Higgs field, to meet the slow-roll conditions would be required.

In this paper, we will first reconsider the analysis of stability and metastability of the SM electroweak vacuum, in view of the most recent experimental results and theoretical developments; and secondly, we will do it for the case where the Higgs is non-minimally coupled to gravity. For the central values of the relevant experimental inputs, which are the strong coupling constant with five flavors, $\alpha_s^{(5)}$, the top quark pole mass, m_t, and the Higgs mass, m_H, in the SM potential a barrier arises between the electroweak minimum and a second high scale minimum. We study in detail the phenomenology of such a barrier, as its height and position. Fixing $\alpha_s^{(5)}$

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arXiv:2403.02425v1 [hep-ph] 4 Mar 2024

CFTP/24-001

Prepared for submission to JHEP

Impact of New Experimental Data on the C2HDM: the Strong Interdependence between LHC Higgs Data and the Electron EDM

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Abstract: The complex two-Higgs doublet model (C2HDM) is one of the simplest extensions of the Standard Model with a source of CP-violation in the scalar sector. It has a $\mathbb{Z}_2$ symmetry, softly broken by a complex coefficient. There are four ways to implement this symmetry in the fermion sector, leading to models known as Type-I, Type-II, Lepton-Specific and Flipped. In the latter three models, there is *a priori* the surprising possibility that the 125 GeV Higgs boson couples mostly as a scalar to top quarks, while it couples mostly as a pseudoscalar to bottom quarks. This "maximal" scenario was still possible with the data available in 2017. Since then, there have been more data on the 125 GeV Higgs boson, direct searches for CP-violation in angular correlations of τ-leptons produced in Higgs boson decays, new results on the electron electric dipole moment, new constraints from LHC searches for additional Higgs bosons and new results on $b \to s\gamma$ transitions. Highlighting the crucial importance of the physics results of LHC's Run 2, we combine all these experiments and show that the "maximal" scenario is now excluded in all models. Still, one can have a pseudoscalar component in $h\tau\bar{\tau}$ couplings in the Lepton-Specific case as large as 87% of the scalar component for all mass orderings of the neutral scalar bosons.

CTPU-PTC-24-06

Cogenesis of baryon and dark matter with PBH and QCD axion

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arXiv:2403.02401v1 [hep-ph] 4 Mar 2024

Abstract

We study the role of an ultra-light primordial black hole (PBH) dominated phase on the generation of baryon asymmetry of the Universe (BAU) and dark matter (DM) in a type-I seesaw framework augmented by Peccei-Quinn (PQ) symmetry which solves the strong CP problem. While the BAU is generated via leptogenesis from the decay of heavy right-handed neutrino (RHN) at the seesaw scale dictated by the PQ scale, DM can arise either from QCD axion or one of the RHNs depending upon the PQ scale. The ultra-light PBH not only affects the axion DM production via misalignment mechanism, but can also produce superheavy RHN DM via evaporation. Depending upon the PBH parameters and relative abundance of axion DM, axion mass can vary over a wide range from sub-μeV to sub-eV keeping the detection prospects promising across a wide range of experiments. While hot axions produced from PBH evaporation can lead to observable $\Delta N_{\rm eff}$ to be probed at future cosmic microwave background (CMB) experiments, stochastic gravitational waves (GW) produced from PBH density fluctuations can be observed at future detectors like CE, DECIGO, LISA and even future runs of LIGO-VIRGO.

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MAX-PLANCK-MEDAILLE

Expedition to the Zeptouniverse

Flavour experiments promise insights into energy scales as high as 200 TeV and distances as small as 10^{-21} meter and offer the chance to identify New Physics.

Andrzej J. Buras

The Large Hadron Collider (LHC) at CERN will directly probe distance scales as short as 10^{-19} m, corresponding to energy scales at the level of a few TeV. Presently, higher resolution can only be achieved with the help of quantum fluctuations caused by new particles and new forces that act at very short distance scales and modify the predictions of the Standard Model of particle physics for very rare processes. In this context, weak decays of mesons and leptons play the prominent role besides the transitions between particles and antiparticles in which flavours of quarks and leptons are changed. In this manner, information about the Zeptouniverse corresponding to energy scales as high as 200 TeV or distances as small as 10^{-21} m can be obtained.

The year 1676 was very important for humanity, because Antoni van Leeuwenhoek discovered the empire of bacteria. He called these small creatures *animalcula* (small animals). His discovery was a milestone in our civilization for at least two reasons: He discovered creatures invisible to us which have been killing humans for thousands of years, often responsible for millions of deaths in one year. While Antoni van Leeuwenhoek did not know that bacteria could be dangerous for humans, his followers like Louis Pasteur, Robert Koch and other „microbe hunters“ realized the danger coming from these tiny creatures and also developed weapons against this empire [1].

Van Leeuwenhoek was the first human who looked at short distance scales invisible to us and discovered thereby

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KCL-PH-TH/2024-09

Vector Wave Dark Matter and Terrestrial Quantum Sensors

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Abstract: (Ultra)light spin-1 particles—dark photons—can constitute all of dark matter (DM) and have beyond Standard Model couplings. This can lead to a coherent, oscillatory signature in terrestrial detectors that depends on the coupling strength. We provide a signal analysis and statistical framework for inferring the properties of such DM by taking into account (i) the stochastic and (ii) the vector nature of the underlying field, along with (iii) the effects due to the Earth's rotation. On time scales shorter than the coherence time, the DM field vector typically traces out a fixed ellipse. Taking this ellipse and the rotation of the Earth into account, we highlight a distinctive three-peak signal in Fourier space that can be used to constrain DM coupling strengths. Accounting for all three peaks, we derive latitude-independent constraints on such DM couplings, unlike those stemming from single-peak studies. We apply our framework to the search for ultralight $B-L$ DM using optomechanical sensors, demonstrating the ability to delve into previously unprobed regions of this DM candidate's parameter space.

arXiv:2403.02381v1 [hep-ph] 4 Mar 2024