The Strong CP Problem in the Quantum Rotor

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Recent studies have claimed that the strong CP problem does not occur in QCD, proposing a new order of limits in volume and topological sectors when studying observables on the lattice. In order to shed light on this issue, we study the effect of the topological θ-term on a simple quantum mechanical rotor that allows a lattice description. The topological susceptibility and the θ-dependence of the energy spectrum are both computed using local lattice correlation functions. The sign problem is overcome by considering Taylor expansions in θ exploiting automatic differentiation methods for Monte Carlo processes. Our findings confirm the conventional wisdom on the strong CP problem.

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I. INTRODUCTION

The strong CP problem remains as one of the puzzles of the Standard Model: why do the strong interactions conserve CP? In principle, the Lagrangian of Quantum Chromodynamics (QCD) admits a renormalizable gauge invariant θ-term,

$$\delta\mathcal{L}_\theta = \frac{\theta}{16\pi^2}\mathrm{tr}\left(F_{\mu\nu}\tilde{F}^{\mu\nu}\right), \tag{1}$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu + [A_\mu, A_\nu]$ is the field strength and A_μ the gauge connection. While the presence of such a term would break CP symmetry in QCD, experimental measurements of the electric dipole moment of the neutron constrain the coupling to be $|\theta| \lesssim 10^{-10}$ [1].

Many solutions have been proposed over the years. The existence of a massless quark would make the θ phase unphysical, but recent lattice simulations clearly disfavor such a solution [2]. Additionally, various alternatives beyond the Standard Model, such as a Peccei-Quinn symmetry [3] and Nelson-Barr type models [4, 5], have been explored.

It has been claimed in refs. [6, 7] that the effect of a such a θ-term, even if present, would not lead to observable consequences. These works argue that when computing correlation functions, the infinite volume limit should be taken *before* the summation over topological sectors. The consequence of such an order of limits (infinite volume at each fixed topological charge) would be the absence of θ-dependence from observables, and particularly from the energy spectrum of the theory.

We claim that, in fact, the order of limits is only important if one insists in computing *global* observables, i.e. those computed as an integral over the whole Euclidean space. Determining these observables requires extreme care with the role of boundary conditions and in taking the infinite volume limit. On the other hand they also represent quite unphysical setups, since we do not need to know the boundary conditions of the universe to measure the topological susceptibility, the proton mass, or the neutron electric dipole moment: all physical quantities of interest can be extracted from local correlators. Due to clustering, the dependence of local correlators on the boundary conditions or the finite volume is exponentially suppressed in theories with a mass gap, making the order of limits largely irrelevant.

In this paper, we aim to shed some light on this question by examining a simple toy model that, nevertheless, shares some key characteristics with QCD: the quantum rotor. We will compute the topological susceptibility from local correlators and show that, up to finite volume corrections, the result is independent of the choice of boundary conditions. The analytical computations will also be supported by numerical lattice simulations,[1] validating the approach used by the lattice community to answer these questions in QCD [8–10]. Additionally, we will determine the topological susceptibility using *master field* simulations [11], where a single gauge configuration in a very large Euclidean volume allows to determine expectation values as volume averages. Both local computations give the same non-zero value for the topological susceptibility, χ_t. Moreover, we will show that the spectrum of the theory has a dependence on θ.

Finally, the numerical study of this rather simple system faces several challenging problems present in lattice QCD. We will use several recent proposals to overcome these problems, making the study of this particular model a good test-bed for many state-of-the-art lattice techniques. Firstly, the issue of *topology freezing* [12–15] when approaching the continuum limit is solved by the use of winding transformations [16]. Secondly, simulating the theory at a non-zero value of θ leads to the so-called *sign problem* —see [17, 18] and references therein. We employ three different methods to overcome this, which

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[1] The code used for the simulations and analysis can be found in https://github.com/dalbandea/QuantumRotorExperiments.jl and https://igit.ific.uv.es/gtelo/qrotor.

GW Backgrounds associated with PBHs

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PBH formation requires high-density regions in the (random) density field filling the primordial universe. While only the largest (and so rarest) overdensities collapse to form PBHs, the rest cause large anisotropic stresses, which are the source of GWs. We provide an overview of the theoretical aspects of the GW backgrounds associated with PBHs from large primordial fluctuations. We consider GW backgrounds associated with PBH formation, PBH reheating and unresolved PBH binaries. We present several graphical summaries and illustrations for the busy reader.

I. INTRODUCTION

Whenever there are fluctuations on top of the isotropic and homogeneous primordial universe, there is a secondary generation of GWs. Kenji Tomita was the first to write about this effect in the '70s in Ref. [1], saying that "gravitational waves are induced by deformed density perturbations". Our interpretation of Ref. [1] is that by "deformed density perturbations" Tomita meant the anisotropic stress resulting from the presence of density perturbations. This will be clear later from Fig. 1. This effect, which we will call induced GWs, was later studied in the '90s by Matarrese, Pantano and Saez [2, 3] and by Matarrese, Mollerach and Bruni [4]. Ten years later, in 2006, we find a glimpse of the potential of induced GWs by Ananda, Clarkson and Wands [5], where they considered an "excess power in a single mode" from the power spectrum measured by CMB observations (and also using a notation very similar to the current one). A very nice work by Baumann, Steinhardt, Takahashi and Ichiki [6] hinted that induced GWs could be enhanced during a matter-dominated phase (see also Refs. [7, 8]). But, it was not until 2008 that Saito and Yokoyama [9, 10] made the connection between induced GWs and PBHs. Their idea was quickly followed by Bugaev and Klimai [11–13]. For more details on the early history of induced GWs and recent developments, we refer the reader to Ref. [14] for a recent review on the topic by the author of this chapter. Other helpful reviews can be found in Refs. [15–18].

Induced GWs are a crucial observable for any PBH scenario. As it will be evident by the end of this chapter, an induced GW background must be present if there is (or was) a significant fraction of PBHs in the universe. Though the opposite is not always true, the induced GW background might suggest, or strongly exclude, PBHs as a significant fraction of DM. This chapter will aim to introduce the main formulas and predictions for the GW backgrounds associated with PBHs, focusing on a qualitative and intuitive understanding of the physics behind such GWs and the

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Positivity in Amplitudes from Quantum Entanglement

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We show that positivity of the imaginary part of forward elastic amplitudes for perturbative scattering is equivalent to consistency of the entanglement generated by the S-matrix, for states with arbitrary internal quantum numbers such as flavor. We also analyze "disentanglers," certain highly entangled initial states for which the action of the S-matrix is to decrease subsystem entanglement.

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Introduction.—Scattering amplitudes are among the most foundational and compelling observables in physics. As the fundamental objects of study in quantum field theory, their structure underpins much of modern high-energy physics, from phenomenology to string theory. The mathematical structure of amplitudes has been studied for decades, and important theorems arising from unitarity and locality are well known, including constraints on their asymptotic growth and analytic structure, e.g., the bounds of Froissart, Martin, Lehmann, et al. [1–3]. Moreover, in the modern amplitudes program, it has been shown that unitarity and locality themselves can emerge from more primordial mathematical structures [4, 5].

Chief among the many useful and famous facts about scattering amplitudes is the optical theorem, which relates the imaginary part of an amplitude—at forward kinematics, where the outgoing and incoming states are identical and particles pass straight through each other—to its cross section. Systematic use of this fact, dubbed "positivity" of amplitudes, has especially in the last two decades allowed the laws of physics themselves to be constrained using analytic dispersion relations, implying numerous different bounds on the space of coefficients of higher-dimension operators in effective field theories (EFTs) [6–10], ranging from the standard model EFT [11–16] to quantum corrections to gravity [17–21].

Meanwhile, entanglement is the quintessentially novel property of quantum mechanics [22, 23]. Historically, it was experimentally verified in classic laboratory demonstrations of violations of Bell's inequality [23, 24]. Excitingly, the highest-energy probes of entanglement can now be implemented in colliders, such as measurements of spin entanglement in top quark systems recently observed by the ATLAS Collaboration at the LHC [25] as proposed in Ref. [26]; see also Refs. [27–30]. These measurements open novel directions in constraining possible new physics using quantum information [31–33].

Quantum information theory also provides many positivity bounds on physics of an a priori different sort than dispersion relations. These bounds take the form of inequalities on quantum entanglement, that is, the von Neumann entropy $S(\hat{\rho}) = -\mathrm{Tr}[\hat{\rho}\log\hat{\rho}]$ for a density matrix $\hat{\rho}$. Various such bounds can be derived from quantum mechanics alone as consequences of linear algebra, including monogamy of entanglement, subadditivity, strong subadditivity, the Araki-Lieb inequality, etc. [34]. By considering other quantum information theoretic measures, such as relative entropy, yet more relations can be found [35]. In addition, entanglement entropy for states of conformal field theories with holographic spacetime duals are subject to additional bounds, such as monogamy of mutual information [36] or reflected entropy inequalities [37, 38], which can be proved geometrically via the AdS/CFT correspondence. Underpinning all of these results is the basic requirement of positivity of entanglement entropy, $S(\hat{\rho}) \geq 0$.

An interesting question is whether these two notions of positivity—that is, the amplitudes' positivity and entanglement entropy—can be related. Do quantum information bounds place additional constraints on EFTs? Or is the optical theorem somehow itself a statement about the entanglement structure of the S-matrix? While there are many realizations of the unitarity in quantum field theory, in this paper we aim to connect those associated with these two manifestations of positivity. The intersection of quantum entanglement and the S-matrix has not been fully investigated, though there have been interesting observations made about the relation between entanglement extremization and low-energy emergent symmetries [39–43], as well as between entanglement and the Yang-Mills/gravity double copy [44]. In notable work, Ref. [45] considered the quantum Tsallis entropy and showed that, subject to certain conditions on an unentangled initial state, it grows under perturbative scattering. The deeper question of whether positivity of the quantum entanglement itself can *imply* amplitudes' positivity, in a broader context of states with general quantum numbers, has not been explored. This question—focusing on discrete Hilbert spaces and asking the converse of whether positivity can emerge from entanglement—is especially interesting from both a quantum computing and phenomenological standpoint, as many particles in the standard model possess flavor or polarization.

In this Letter, we address this problem and show that

Effective Potential and Vacuum Stability in the Litim-Sannino Model

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Abstract: We revisit the scalar potential in the Litim-Sannino model. We compute for the first time the full quantum corrections to the classical potential and show that they significantly ameliorate the stability analysis at the UV fixed point. The quantum effective potential is computed at two-loop order and the numerical precision is further improved using resummations and parameter optimisations. As a result, we find a consistent widening of the UV conformal window across various approximations.

Negative magnetoresistance induced by longitudinal photons in Dirac/Weyl semimetals.

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A low-energy model is built to study systems such as Dirac/Weyl semimetals, according to statistical quantum electrodynamics formalism. We report that the introduction of a pseudoscalar, associated to longitudinal photons propagating along a magnetic field **B**, could transforms a Dirac semimetal into a Weyl semimetal with a pair of Weyl nodes for each point of Dirac. The nodes are separated by a pseudovector electric field induced dynamically along **B** associated to a chiral effect on the Fermi surface. A topological quantum transition is produced between a chiral-and non chiral symmetry phase. A general expression to the longitudinal magnetoconductivity is found. It provides the possibility of generalizing the usual expressions of the magnetoconductivity reported in the literature. This has a quadratic dependence on **B**, which is associated with a positive contribution to the magnetoconductivity. This is a prominent signature of the chiral magnetic effect in Dirac/Weyl systems in parallel electric and magnetic fields. We report a chiral effect induced by longitudinal photons associated to a negative longitudinal magnetoresistance in Dirac systems via an axial anomaly relation. We show some numerical results, and reproduced with a high level of accuracy some of the experimental results, in the low temperature region, obtained to the magnetoresistance of $ZrTe_5$ and Na_3Bi. We believe that a wide variety of these semimetals can be studied by using our general expression to the negative longitudinal magnetoresistance.

Keywords: Dirac/Weyl semimetals−negative longitudinal magnetoresistance−chiral symmetry breaking−statistical quantum electrodynamics

I. INTRODUCTION

Nowadays the influence of the magnetic fields in relativistic quantum systems, like the three-dimensional $(3 + 1)$ Dirac semimetals: cadmium arsenide (Cd_3As_2), trisodium bismuthide (Na_3Bi)[1–4] and zirconium pentatelluride ($ZrTe_5$)[5] has enabled experimental studies of the quantum dynamics of relativistic field theory in condensed matter systems. The relativistic theory of charged chiral fermions in three spatial dimensions possesses the so-called chiral anomaly (discussed by Adler-Bell-Jackiw[6,7]), that is, non-conservation of chiral charge induced by gauge fields with non-trivial topology, for example, by parallel electric and magnetic fields. The existence of chiral quasiparticles in Dirac and Weyl semimetals opens the possibility to observe the effects of the chiral anomaly in magnetized low-energy systems.

Weyl and Dirac semimetals are three dimensional phases of matter with gapless electronic excitations that are protected by topology and symmetry. As the three dimensional analogs of graphene the semimetals have low-energy quasiparticles near the Fermi surface, which are described by the Dirac and Weyl equations respectively[8–10]. The Bismuth is an example of a semimetal whose effective theory at low-energies includes Dirac fermions in $3 + 1$ dimensions[11]. Their electronic states in the vicinity of the Weyl nodes have a definite chirality, which is found associated with unique topological and electromagnetic properties.

In the absence of any symmetry one could obtain accidental two-fold degeneracies of bands in a three dimensional solid[12]. The dispersion in the vicinity of these band touching points is generically linear and is given by the Weyl equation. Perhaps, the best known example is the graphene, where a linear dispersion relation is obtained by the two dimensional massless Dirac equation. These two-dimensional $(2 + 1)$ carbon sheets provide a condensed matter analogue of a $2+1$-dimensional quantum electrodynamics[13]. Remarkably several of the defining physical properties of Weyl fermions, such as the so-called chiral anomaly, continue to hold in this non relativistic condensed matter context. The Adler-Bell-Jackiw anomaly can have nontrivial effects as pointed out in[14], which established the link between band touchings in three dimensional crystals, named Weyl nodes[8], and chiral fermions.

On the other hand the discovery of topological insulators in two and three dimensions[15–25], has led to an explosion of activity in the study of topological aspects of band structures[26–28]. These have interesting connections to gapless states. The surfaces of topological insulators in $3+1$ feature a gapless Dirac dispersion, analogous to the two dimensional semimetal graphene, but with important differences in the number of nodal points. The transition between topological and trivial phases proceeds through a gapless state. For example a $3 + 1$ topological to trivial insulator transition proceeds through the $3 + 1$ Dirac dispersion, in the presence of both time reversal and inversion symmetry[29].

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Cluster Scanning: a novel approach to resonance searches

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Abstract: We propose a new model-independent method for new physics searches called Cluster Scanning. It uses the k-means algorithm to perform clustering in the space of low-level event or jet observables, and separates potentially anomalous clusters to construct a signal-enriched region. The invariant mass spectra in these two regions are then used to determine whether a resonant signal is present. A pseudo-analysis on the LHC Olympics dataset with a Z' resonance shows that Cluster Scanning outperforms the widely used 4-parameter functional background fitting procedures, reducing the number of signal events needed to reach a 3σ significant access by a factor of 0.61. Emphasis is placed on the speed of the method, which allows the test statistic to be calibrated on synthetic data.

Dual chiral density wave induced oscillating Casimir effect

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The Casimir effect is known to be induced from photon fields confined by a small volume, and also its fermionic counterpart has been predicted in a wide range of quantum systems. Here, we investigate what types of Casimir effects can occur from quark fields in dense and thin quark matter. In particular, in the dual chiral density wave, which is a possible ground state of dense quark matter, we find that the Casimir energy oscillates as a function of the thickness of matter. This oscillating Casimir effect is regarded as an analog of that in Weyl semimetals and is attributed to the Weyl points in the momentum space of quark fields. In addition, we show that an oscillation is also induced from the quark Fermi sea, and the total Casimir energy is composed of multiple oscillations.

I. INTRODUCTION

The Casimir effect, proposed by Casimir [1], is crucially important for understanding small-volume physics in quantum field theory (see Refs. [2–6] for reviews). Casimir predicted that the decrease of the zero-point energy of photon fields by two parallel plates would cause an attractive force for the plates, which are the so-called Casimir energy and the Casimir force. The Casimir force was experimentally verified about fifty years later [7, 8].

Beyond academic interest, the engineering application of the Casimir effect to nanotechnology (Casimir engineering) has recently attracted much attention [9]. The most typical feature of the Casimir effect is an attractive force. On the other hand, when one tunes the permittivity and/or permeability of plates and medium, a repulsive force can be also realized [10–13]. In contrast to such attractive or repulsive Casimir effects, it would be interesting that the third type of Casimir effect, where "third" means that attraction or repulsion is not fixed. For example, under a setup, the sign of Casimir energy flips from attraction to repulsion as the separation distance increases, which may be called the *sign-flipping Casimir effect* (e.g., see Refs. [14–19]). As another example, the value of Casimir energy can oscillate as a function of distance, which may be called the *oscillating Casimir effect* (e.g., see Refs. [20–32]). Among them, Ref. [31] found that it occurs inside Weyl semimetals, where the origins of the oscillation are Weyl points (WPs) at finite momenta in the dispersion relations of Weyl fermions. Such new types of Casimir effects are not only of theoretical interest but also will be important for Casimir engineering.

The Casimir effect is also important for elucidating quark and gluon dynamics described by Quantum Chromodynamics (QCD) in a small volume. For example, (i) as an ab initio method for solving QCD, numerical simulations of lattice QCD are done in finite volume (e.g., in a box of a few fm size), and finite-volume effects must be understood. Since the finite-volume effect for zero-point energy is nothing but the Casimir effect, its understanding is helpful for interpretations of results in small-volume simulations. (ii) In relativistic heavy-ion collision experiments, quark-gluon plasma is produced as a fireball with a size of a few fm. Therefore, we must well understand the contribution of the Casimir effect to physics inside the fireball and near its boundary. (iii) In the interiors of neutron stars, dense quark matter as well as nuclear matter may exist. Depending on the microscopic density profile inside stars, there may be small regions of quark matter.

Under these motivations, this paper focuses on what types of Casimir effects can occur in various phases of quark matter where the thickness of z direction is extremely short (i.e., "thin" quark matter) as illustrated in Fig. 1. In particular, in this paper, we propose a QCD

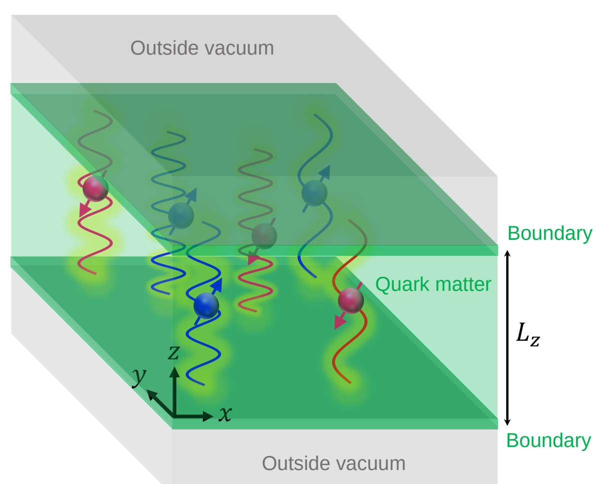

FIG. 1. Schematics of the Casimir effect for quark fields inside thin quark matter, where the quark matter is confined between boundary conditions with a thickness L_z. The "outside vacuum" should be regarded as an arbitrary vacuum consistent with the boundary conditions.

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Triangle singularity in the $J/\psi \to \phi\pi^+ a_0^-(\pi^-\eta)$, $\phi\pi^- a_0^+(\pi^+\eta)$ decays

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Abstract

We study the $J/\psi \to \phi\pi^+ a_0(980)^-(a_0^- \to \pi^-\eta)$ decay, evaluating the double mass distribution in terms of the $\pi^-\eta$ and $\pi^+ a_0$ invariant masses. We show that the $\pi^-\eta$ mass distribution exhibits the typical cusp structure of the $a_0(980)$ seen in recent high statistics experiments, and the $\pi^+ a_0$ spectrum shows clearly a peak around $M_{\rm inv}(\pi^+ a_0) = 1420\,\mathrm{MeV}$, corresponding to a triangle singularity. When integrating over the two invariant masses we find a branching ratio for this decay of the order of 10^{-5}, which is easily accessible in present laboratories.

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Quasi-Classical Gluon Fields and Low's Soft Theorem at Small x

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In the high energy limit, soft gluons can be approximately described by quasi-classical gluon fields. It is well-known that the gluon field is a pure gauge field on the transverse plane at eikonal order. We derived the complete next-to-eikonal order solutions of the classical Yang-Mills equations for soft gluons in the dense nuclear regime. Utilizing these solutions, it is shown that Low's soft theorem at small x can be obtained by considering off-diagonal matrix elements of quasi-classical chromoelectric field between single gluon states in the dilute regime. Furthermore, we extend Low's soft theorem at small x to incorporate the effects of gluon saturation in the dense regime.

Introduction. Using quasi-classical gluon fields to characterize soft gluons particularly in small x physics has a long history [1]. In the high energy limit, nuclear objects are highly Lorentz contracted along the longitudinal direction so that a two-dimensional shockwave picture becomes applicable in describing high energy collisions [2]. In the McLerran-Venugopalan (MV) model [3, 4] , soft gluon fields from large nuclei are solved from the classical Yang-Mills equations with color current sourced by hard gluons. This eikonal order quasi-classical gluon fields, valid in the parametrically dense regime $\mathcal{O}(1/g)$ in which nonlinear QCD interactions cannot be ignored [5, 6], was used to estimate the Weiszacker-Williams gluon distribution inside a large nucleus in the quasi-classical approximation [7]. Phenomenological applications in relativistic heavy-ion collisions [8–15] and high energy proton-nucleus collisions [16–19] using the classical field approach were actively pursued in the past three decades [20] .

Quasi-classical gluon field at eikonal order is insensitive to spin information of the nuclear object. To study spin related physical quantities particularly to understand the spin structure of proton at small x [21, 22], subeikonal order gluon field is needed. There have been a lot of efforts in recent years to identify the effective interactions at subeikonal order [23–29] and to derive small x evolution equations for polarized parton distributions inside proton/nucleus [30–35]. Notably, the spin-dependent part of subeikonal order quasi-classical gluon fields was obtained using a diagrammatic approach in covariant gauge in [36].

In this paper, we derived the complete solutions at subeikonal order for quasi-classical gluon fields including both spin-dependent and spin-independent parts in the dense nuclear regime. The solutions are presented in the covariant gauge as well as in the light-cone gauge. We found that, in addition to the piece found in [36], there exists a novel spin-dependent term induced by gluon saturation, which becomes significant only in the dense regime. The spin-independent part bears resemblance to the next-to-leading-order magnetic multipole expansion in two dimensions, as inferred from Ampere's law. Regarding the external color currents originating from hard gluons, our findings indicate that, apart from the color charge density at subeikonal order, the color spin density and transverse color current also serve as sources for the quasi-classical gluon fields.

A closely related topic to soft gluons involves Low's soft theorem [37–41], which states that at amplitude level, the radiative amplitude can be expressed as a factorized product of a soft factor and the nonradiative amplitude when taking the soft limit. In the past decades, there have been reviving interests in understanding Low's soft theorem in the Standard Model of particle physics and gravity from the perspective of asymptotic symmetries [42–44]. Subleading order Low's soft theorem was rederived from various approaches [45–48]. Our focus lies on the small x limit of the subleading order Low's soft theorem. We demonstrate that the classical field approach effectively reproduces the small x limit of Low's soft theorem up to subleading order. Specifically, the matrix element of quasi-classical chromoelectric fields between incoming and outgoing single gluon states in the dilute limit coincides with Low's soft theorem at small x. The classical field approach offers more as it allows for solutions in the dense regime, enabling the generalization of Low's soft theorem to incorporate dense gluon effects, thereby linking Low's soft theorem to gluon saturation.

In the following, we first present the details of obtaining complete next-to-eikonal order solutions by solving classical Yang-Mills equations and then establish its equivalence to Low's soft theorem at small x.

Quasi-classical Gluon Fields at Subeikonal Order. We consider a pure glue theory and solve classical Yang-Mills equations. The inclusion of quarks and solving coupled Dirac equation for soft quark fields are left for a future work. Starting from the Yang-Mills action $S = -\frac{1}{4}\int_x F^a_{\mu\nu}F^{\mu\nu,a}$ with $F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + ig[A_\mu, A_\nu]^a$, one separates the full gluon field into soft gluon field $\mathcal{A}_\mu$ and hard gluon field A_μ according to their longitudinal momenta

$$A^a_\mu \to \mathcal{A}^a_\mu + A^a_\mu. \tag{1}$$

Let Λ^+ be some longitudinal momentum scale. Soft gluon fields represent modes with $k^+ \ll \Lambda^+$ while hard gluon

T-odd gluon distribution functions in a spectator model

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We present a model calculation of T-odd transverse-momentum-dependent distributions of gluons in the nucleon. The model is based on the assumption that a nucleon can emit a gluon, and what remains after the emission is treated as a single spectator particle. This spectator particle is considered to be on-shell, but its mass is allowed to take a continuous range of values, described by a spectral function. The final-state interaction that is necessary to generate T-odd functions is modeled as the exchange of a single gluon between the spectator and the outgoing parton.

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CONTENTS

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The ghost-gluon vertex in the presence of the Gribov horizon: general kinematics

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Correlation functions are important probes for the behavior of quantum field theories. Already at tree-level, the Refined Gribov Zwanziger (RGZ) effective action for Yang-Mills theories provides a good approximation for the gluon propagator, as compared to that calculated by nonperturbative methods such as Lattice Field Theory and Dyson-Schwinger Equations. However, the study of higher correlation functions of the RGZ theory is still at its beginning. In this work we evaluate the ghost-antighost-gluon vertex function in Landau gauge at one-loop level, in $d = 4$ space-time dimensions for the gauge groups SU(2) and SU(3). More precisely, we extend the analysis conducted in [1] for the soft-gluon limit to an arbitrary kinematic configuration. We introduce renormalization group effects by means of a toy model for the running coupling and investigate the impact of such a model in the ultraviolet tails of our results. We find that RGZ results match fairly closely those from lattice simulations, Schwinger-Dyson equations and the Curci-Ferrari model for three different kinematic configurations. This is compatible with RGZ being a feasible theory for the strong interaction in the infrared regime.

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I. INTRODUCTION

Since the proposal of Quantum Chromodynamics (QCD) as the theory of Strong Interactions, a long path was constructed to connect the fundamental degrees of freedom – quarks and gluons – to the observed physical states and processes. At high energies, asymptotic freedom allows for a perturbative approach that, supplemented by essential nonperturbative information in Particle Distribution Functions and fragmentation phenomena, agrees with a plethora of experimental output from high-energy particle colliders. The infrared (IR) regime however is much less amenable. Monte Carlo simulations that solve the Euclidean version of QCD on a discretized space-time lattice have by now and with great effort established that this non-Abelian theory can quantitatively describe several hadronic observables [2–5]. Nevertheless, the mechanism of color confinement is still an open question, calling for the development of continuum approaches and (semi)analytical descriptions of the infrared behavior of Strong Interactions. Among the well-developed continuum methods that try to tackle this non-perturbative regime, Schwinger-Dyson equations [6–15] stand out in different hadronic applications, but also the Functional Renormalization Group [16–21] and effective models [22–26] have been employed with partial success. Other approaches, such as the Curci-Ferrari (CF) model in Landau gauge [27–37] and the screened massive expansion [38–42] have successfully described some aspects of the IR of Yang-Mills theory by employing perturbation theory.

Here we adopt another continuum approach to the nonperturbative regime of Yang-Mills theories: the Refined Gribov-Zwanziger (RGZ) theory [43, 44]. This framework, as the other continuum methods, adopts a gauge-fixed setup and is formulated from first-principles as a gauge path integral modified in the infrared by the existence of Gribov gauge copies. This idea follows the seminal work by Gribov himself [45] and the development of local actions attained by Zwanziger [46] and complemented by the emergence of dimension two condensates [43, 44, 47]. For comprehensive reviews, the reader is referred to [48–50] and references therein.

The presence of this nonperturbative background stemming from the Gribov horizon and the condensates seems to carry plenty of information from the interacting theory, so that the remaining interaction corrections might be supposed to be small, *i.e.* perturbative. Even at tree-level, the RGZ gluon propagator is compatible with the deep IR behavior observed on Landau-gauge Lattice QCD data [43], while reducing to pure Yang-Mills at large energies [51] in

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A case study of sending graph neural networks back to the test bench for applications in high-energy particle physics

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Abstract In high-energy particle collisions, the primary collision products usually decay further resulting in tree-like, hierarchical structures with a priori unknown multiplicity. At the stable-particle level all decay products of a collision form permutation invariant sets of final state objects. The analogy to mathematical graphs gives rise to the idea that graph neural networks (GNNs), which naturally resemble these properties, should be best-suited to address many tasks related to high-energy particle physics. In this paper we describe a benchmark test of a typical GNN against neural networks of the well-established deep fully-connected feed-forward architecture. We aim at performing this comparison maximally unbiased in terms of nodes, hidden layers, or trainable parameters of the neural networks under study. As physics case we use the classification of the final state X produced in association with top quark-antiquark pairs in proton-proton collisions at the Large Hadron Collider at CERN, where X stands for a bottom quark-antiquark pair produced either non-resonantly or through the decay of an intermediately produced Z or Higgs boson.

Keywords Graph Neural Networks · Deep Neural Networks · High-Energy Particle Physics · LHC

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A comparative study of flavour-sensitive observables in hadronic Higgs decays

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Abstract Jet production from hadronic Higgs decays at future lepton colliders will have significantly different phenomenological implications than jet production via off-shell photon and Z-boson decays, owing to the fact that Higgs bosons decay to both pairs of quarks and gluons. We compute observables involving flavoured jets in hadronic Higgs decays to three partons at Born level including next-to-leading order corrections in QCD (i.e up to $\mathcal{O}(\alpha_s^2)$). The calculation is performed in the framework of an effective theory in which the Higgs boson couples directly to gluons and massless b-quarks retaining a non-vanishing Yukawa coupling. For the following flavour sensitive observables: the energy of the leading and subleading flavoured jet, the angular separation and the invariant mass of the leading b-$\bar{b}$ pair, we contrast the results obtained in both Higgs decay categories and using either of the infrared-safe flavoured jet algorithms flavour-k_T and flavour-dressing.

Keywords flavoured jets · hadronic Higgs decays · NLO QCD

1 Introduction

Precision studies of the Higgs boson discovered at LHC by CMS and ATLAS [1,2] will become possible at future lepton colliders such as [3,4], all aiming to operate as Higgs factories. In this clean experimental environment, where interactions take place at well-defined centre-of mass energies, it is expected to enable model-independent measurements of the Higgs couplings to gauge bosons and fermions at the level of a few percent. At these future lepton colliders, in particular it will become possible to have access to so-far unobserved hadronic decay channels such as Higgs decays to gluons. The latter is currently inaccessible in hadron-collider environments due to the presence of overwhelming QCD backgrounds. Only the $H \to b\bar{b}$ decay was observed to date [5,6] in associated vector-boson production where the leptonic decay signature of the vector boson helps to identify the $H \to b\bar{b}$ decay.

Hadronic Higgs decays to at least two final state hard partons proceed via two main decay modes; either as Yukawa-induced decay to a bottom-quark pair, $H \to b\bar{b}$, or as a heavy-quark-loop induced decay to two gluons, $H \to gg$. In the latter category, observables are computed in the framework of an effective field theory, in which the top-quark loop is integrated out into an effective point-like Hgg vertex.

So far these two categories of Higgs decay processes have been considered together in the computation of flavour-agnostic event-shape observables, i.e., for three-jet-like final states in [7,8,9,10,11] and for four jet-like final states in [12]. It was also recently suggested to determine branching ratios in hadronic Higgs decays via fractional energy correlators [13]. Flavour-sensitive jet observables related to the presence of a flavoured jet in the final state have so far been computed for the following LHC processes: VH production, with $H \to b\bar{b}$ or $Z + b$-jet and $Z/W + c$-jet, with the vector boson decaying leptonicallly in all cases. More precisely, parton-level predictions including up to NNLO QCD corrections using massless charm or bottom quarks at the origin of the flavoured jet have been computed most re-

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Impact of strong magnetic field, baryon chemical potential, and medium anisotropy on polarization and spin alignment of hadrons

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The recent observation of global polarization of Λ ($\bar{\Lambda}$) hyperons and spin alignment of ϕ and K^{*0} vector mesons create remarkable interest in investigating the particle polarization in the relativistic fluid produced in heavy-ion collisions at GeV/TeV energies. Among other sources of polarization, the Debye mass of a medium plays a crucial role in particle polarization. Any modification brought to the effective mass due to the temperature, strong magnetic field (eB), baryonic chemical potential (μ_B), and medium anisotropy (ξ), vorticity, etc., certainly affects the particle polarization. In this work, we explore the global hyperon polarization and the spin alignment of vector mesons corresponding to the strong magnetic field, baryonic chemical potential, and medium anisotropy. We find that the degree of polarization is flavor-dependent for hyperons. Meanwhile, vector meson spin alignment depends on the hadronization mechanisms of initially polarized quarks and anti-quarks. Medium anisotropy significantly changes the degree of polarization in comparison with the magnetic field and baryon chemical potential.

I. INTRODUCTION

So far, the thermalized state of strongly interacting partons, called quark-gluon plasma (QGP), is probed in heavy-ion collisions through a baseline, the *pp* collisions. It was assumed that QGP existence in *pp* collisions is next to impossible because it lacks the necessary conditions for QGP to be formed. On the contrary, in recent LHC events, ultra- relativistic *pp* collision experiments have reported behavior similar to heavy-ion collisions, e.g., collective flow, strangeness enhancement, etc [1, 2]. However, other studies suggest similar phenomena may arise due to the other QCD processes [3**?** , 4]. These studies raise a question concerning the present QGP signatures and a need for the next generation of probes. In the quest for such a baseline-independent probe, polarization comes into picture and can have implications for understanding hot QCD matter. The particle production mechanisms lead to a finite polarization of the light/heavy baryons and vector mesons [5]. However, there are various sources by which hadrons can get polarized in ultra-relativistic collisions. One such primary source could be the initial state polarization, which arises due to the motion and spin of the constituent quarks of the colliding nucleons. This initial state polarization can be transmitted to the quarks participating in the collision process. The magnetic field produced by the charged spectator protons in such collisions interacts with the electric charge and spin of the quarks, which may lead to quark polarization. A topological charge imbalance in the presence of an external magnetic field leads to the charge separation in the direction of the magnetic field. This phenomenon is known as the chiral magnetic effect (CME) [6, 7]. If QGP exhibits chiral symmetry restoration, then CME could lead to quark polarization along the direction of the magnetic field. A similar phenomenon called chiral vortical effect (CVE) is expected due to the non-zero local vorticity, which also contributes to the hadron polarization [8, 9]. The hydrodynamic behavior or collective motion of QGP can also induce polarization in the quark distribution due to the anisotropic expansion [10, 11]. Determining the precise sources and types of polarization in ultra-relativistic collisions requires sophisticated theoretical studies with corresponding experimental observations.

In 2005, Liang and Wang predicted in non-central heavy-ion collisions, the orbital angular momentum (OAM) of the partonic system polarizes the quarks and anti-quarks through spin-orbit coupling. They asserted that the initial partons created in the collisions could generate a longitudinal fluid shear distribution representing the local relative OAM in the same direction as global OAM at a finite impact parameter. This quark polarization manifests the polarization of the hadrons (with finite spin) along the direction of OAM during the process of hadronization [12–15]. Apart from global polarization of hadrons, such global quark polarization has many observable consequences, such as left-right asymmetry in hadron spectra and global transverse polarization of thermal photons, dileptons, etc. [16, 17]. They have studied the global polarization of hyperons [12] and spin alignment of vector mesons [13] in different hadronization scenarios. Following, in 2013, Becattini et al. predicted the global spin polarization of Λ hyperons due to the OAM-manifested thermal vorticity [18]. Various theoretical predictions of global Λ hyperons polarization by different hydrodynamic and transport models are well agreed with the experimental results available at Relativistic Heavy Ion Collider (RHIC) [19–27]. These hydrodynamic and transport

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Constraining Asymmetric Dark Matter using Colliders and Direct Detection

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Abstract: We reappraise the viability of asymmetric dark matter (ADM) realized as a Dirac fermion coupling dominantly to the Standard Model fermions. Treating the interactions of such a DM particle with quarks/leptons in an effective-interactions framework, we derive updated constraints using mono-jet searches from the Large Hadron Collider (LHC) and mono-photon searches at the Large Electron-Positron (LEP) collider. We carefully model the detectors used in these experiments, which is found to have significant impact. The constraint of efficient annihilation of the symmetric part of the ADM, as well as other observational constraints are synthesized to produce a global picture. Consistent with previous work, we find that ADM with mass in the range 1–100 GeV is strongly constrained, thus ruling out its best motivated mass range. However, we find that leptophilic ADM remains allowed for $\gtrsim 10\,\text{GeV}$ DM, including bounds from colliders, direct detection, and stellar heating. We forecast that the Future Circular Collider for electron-positron collisions (FCC-ee) will improve sensitivity to DM-lepton interactions by almost an order of magnitude.

Gluon GTMDs at nonzero skewness and impact parameter dependent parton distributions

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We investigate the leading twist generalized transverse momentum dependent parton distributions (GTMDs) of the unpolarized and longitudinally polarized gluons in the nucleon. We adopt a light-front gluon-triquark model for the nucleon motivated by soft-wall AdS/QCD. The gluon GTMDs are defined through the off-forward gluon-gluon generalized correlator and are expressed as the overlap of light-cone wave functions. The GTMDs can be employed to provide the generalized parton distributions (GPDs) by integrating out the transverse momentum. The Fourier transform of the GPDs encodes the parton distributions in the transverse position space, namely, the impact parameter dependent parton distributions (IPDs). We also calculate the three gluon IPDs corresponding to the GPDs H^g, E^g and $\widetilde{H}^g$, and present their dependence on x and $b_\perp$, respectively.

I. INTRODUCTION

An outstanding goal in hadron physics is to understand the structure of hadrons in terms of quarks and gluons. The deep inelastic scattering (DIS) is among the key tools to reveal hadronic structure, because one can extract the parton distribution functions (PDFs) [1–4] from such process. The PDFs are functions of the longitudinal momentum fraction, which encode the distributions of longitudinal momentum and polarizations of partons. A more comprehensive picture about the nucleon can be revealed by the transverse momentum dependent parton distributions (TMDs) [5, 6], which encode transverse motion of partons inside the nucleon. TMDs can be extracted from semi-inclusive reactions such as the semi-inclusive deep inelastic scatting (SIDIS) and the Drell-Yan process [7–11]. Besides the TMDs, in the off-forward region a new type of nucleon structure–the so-call generalized parton distributions (GPDs) [12–20]–emerge. It is the extension of the ordinary PDF from the forward scattering region to the off-forward scattering region. The GPDs appear in the description of hard exclusive reactions, such as the deeply virtual Compton scattering(DVCS) and the deeply virtual meson production(DVMP) [13, 16, 17, 19]. Furthermore, the transverse position of partons is encoded in the impact parameter dependent parton distributions (IPDs) [21, 22], which are the Fourier transform of the GPDs [17] at zero skewness with respect to the transverse momentum transfer of the hadron.

The most complete structural information of hadrons is contained in the so-called generalized transverse momentum dependent parton distributions (GTMDs) [23, 24], which are often considered as the "mother distributions", since several GTMDs can project to the TMDs and the GPDs in certain kinematical limits. The quark GTMDs may be measurable in the exclusive double Drell-Yan process [25], while the feasibility to measure the gluon GTMDs in the diffractive dijet production has been studied [26–29].

The first complete classification of various parton distributions and their relations with each other has been discussed in Refs. [23, 24]. There are sixteen twist-2 GTMDs for the quark and the gluon in the nucleon, respectively. These GTMDs encode the information of the distributions of the unpolarized and polarized partons. They are characterized by revealing the nucleon spin structure, for example, $F_{1,4}$ and $G_{1,1}$ play an important role in describing the canonical orbit angular momentum (OAM) [30–33] and the spin-orbit correlations [34, 35] of partons, respectively. The quark GTMDs for the nucleon have been calculated in various models, such as the light-cone constituent quark model [30, 36, 37], the light-front dressed quark model [38–40], the light-cone spectator model [41], the light-front quark-diquark model [42–47], the chiral soliton model [30, 36] and the quark target model [48], and so have these distributions for the pion [49–52]. In addition, the importance of the IPDs lies in their physical interpretation as a probability density in the impact parameter space. The quark IPDs for hadrons have been studied in Refs. [22, 53]. However, the theoretical study on the gluon GTMDs and IPDs is still not sufficient.

It should be noted that most of the previous calculations for the GTMDs are made by assuming that the skewness ξ is 0. However, most of the data probed in the experiments is at $\xi \neq 0$. Therefore, a more detailed investigation of the GTMDs at nonzero skewness is necessary. In this work, we investigate the leading twist GTMDs of the unpolarized and longitudinally polarized gluons in the nucleon using the soft-wall AdS/QCD model [54, 55]. This model has been widely applied to the calculations of the PDFs, form factors and mass spectrum [56]. In the description of hadronic form factors at large Q^2 [56–59], the soft wall AdS/QCD embodies a main advantage, namely, the analytical

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Direct Detection of Dark Photon Dark Matter with the James Webb Space Telescope

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Abstract

In this study, we propose an investigation into dark photon dark matter (DPDM) within the infrared frequency band, utilizing highly sensitive infrared light detectors commonly integrated into space telescopes, such as the James Webb Space Telescope (JWST). The presence of DPDM induces electron oscillations in the reflector of these detectors. Consequently, these oscillating electrons can emit monochromatic electromagnetic waves with a frequency almost equivalent to the mass of DPDM. By employing the stationary phase approximation, we can demonstrate that when the size of the reflector significantly exceeds the wavelength of the electromagnetic wave, the contribution to the electromagnetic wave field at a given position primarily stems from the surface unit perpendicular to the relative position vector. This simplification results in the reduction of electromagnetic wave calculations to ray optics. By applying this concept to JWST, our analysis of observational data demonstrates the potential to establish constraints on the kinetic mixing between the photon and dark photon within the range [10, 500] THz. Despite JWST not being optimized for DPDM searches, our findings reveal constraints comparable to those obtained from the XENON1T experiment in the laboratory, as well as astrophysical constraints from solar emission. Additionally, we explore strategies to optimize future experiments specifically designed for DPDM searches.

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Estimation of the electromagnetic field in intermediate-energy heavy-ion collisions

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We estimate the spacetime profile of the electromagnetic field in head-on heavy-ion collisions at intermediate collision energies $\sqrt{s_{\rm NN}} = \mathcal{O}(3\text{ - }10\ \text{GeV})$. Using a hadronic cascade model (JAM; Jet AA Microscopic transport model), we numerically demonstrate that the produced field has strength $eE = \mathcal{O}((30\text{ - }60\ \text{MeV})^2)$, which is supercritical to the Schwinger limit of QED and is non-negligibly large compared even to the hadron/QCD scale, and survives for a long time $\tau = \mathcal{O}(10\ \text{fm}/c)$ due to the baryon stopping. We show that the produced field is nonperturbatively strong in the sense that the nonperturbativity parameters (e.g., the Keldysh parameter) are sufficiently large, which is in contrast to high-energy collisions $\sqrt{s_{\rm NN}} \gtrsim 100$ GeV, where the field is merely perturbative. Our results imply that the electromagnetic field may have phenomenological impacts on hadronic/QCD processes in intermediate-energy heavy-ion collisions and that heavy-ion collisions can be used as a new tool to explore strong-field physics in the nonperturbative regime.

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I. INTRODUCTION

Super dense matter, such as that realized inside a neutron star or even denser, can be produced on Earth by colliding heavy ions at intermediate collision energies $\sqrt{s_{\rm NN}} = \mathcal{O}(3\text{ - }10\ \text{GeV})$. Such collision experiments have been performed in the Beam Energy Scan program at RHIC [1] and are planned worldwide (e.g., FAIR [2], NICA [3], HIAF [4], J-Parc-HI [5]) to reveal the extreme form of matter in the dense limit and to develop a better understanding of strong interaction, or quantum chromodynamics (QCD). These experimental programs have motivated various theoretical studies, which are mainly aimed at investigating the consequences of the high-density matter and the dynamics of how it can be created during the collisions, e.g., novel phases of QCD at finite density (see Ref. [6] for a review) and the development of various transport models to simulate the real-time collision dynamics such as RQMD [7], UrQMD [8, 9], JAM [10], and SMASH [11].

The purpose of this paper is, rather than pursuing the high-density physics as previously discussed, to point out that a strong electromagnetic field can be created in intermediate-energy heavy-ion collisions. The generation of such a strong electromagnetic field is of interest not only to hadron/QCD physics but also to the area of strong-field physics. For hadron/QCD physics, electromagnetic observables such as di-lepton yields [12–15], which are promising probes of nontrivial processes induced by the high-density matter, are naturally affected by the presence of a strong electromagnetic field. A correct estimation of the electromagnetic-field profile (and also its implementation into transport-model simulations; cf. Ref. [16, 17]) is, therefore, important when extracting/interpreting signals of the high-density matter from the actual experimental data. As for strong-field physics, the generation of a strong electromagnetic field would provide a unique and novel opportunity to study quantum electrodynamics (QED) in the nonperturbative regime beyond the Schwinger limit $eE_{\rm cr} := m_e^2 = (0.511\ \text{MeV})^2$ (with $e = |e|$ being the elementary electric charge, E electric field strength, and m_e the electron mass). Currently, strong-field physics is driven mainly by high-power lasers (see, e.g., Refs. [18, 19] for reviews). The focused laser intensity of $I = 1\times10^{23}\ \text{W/cm}^2$ (corresponding to $E \approx 10^{-3}\,E_{\rm cr}$) is the current world record [20], which is envisaged to be surpassed by the latest and future facilities such as Extreme Light Infrastructure (ELI) $I = \mathcal{O}(10^{25}\ \text{W/cm}^2)$ [21]. Although the laser intensity is growing rapidly, it is and will remain, for at least the next decade, several orders of magnitude below the Schwinger limit $E_{\rm cr}$. Therefore, it is difficult to study strong-field phenomena with current lasers. This means that a novel method or physical system to realize a strong electromagnetic field is highly demanded.

There exist a number of studies on the generation of a strong electromagnetic field at low- and high-energies both theoretically and experimentally. Let us briefly review them, so as to clarify our motivation to go to the intermediate energy. At low energies, due to the baryon stopping (i.e., the Landau picture [22, 23]), the collided ions stick together at the collision point and form up a gigantic ion with large atomic number $Z = \mathcal{O}(100)$, and thereby creates a strong Coulomb electric field of the order of $eE \sim (e^2/4\pi)Z/R^2 = \mathcal{O}((20\ \text{MeV})^2)$, where $R = \mathcal{O}(10\ \text{fm})$ is the typical radius of the gigantic ion. The produced field is weak compared to the hadron/QCD scale but is far surpassing the Schwinger limit of QED. Thus, it is expected to induce intriguing nonlinear QED processes such as the vacuum decay (see Ref. [24] for a recent analysis), experimental investigation of which has been done around 1980s but is not conclusive yet (see, e.g., Ref. [25] for possible interpretations of the experimental results). On the other hand, at high energies, the Bjorken picture [26] is valid rather than the Landau picture. The colliding ions penetrate with each other

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PROCEEDINGS OF SCIENCE

Theoretical Highlights of CP Violation in B Decays

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In this presentation, we discuss recent key topics in theoretical analyses of CP violation in benchmarks decays of the B meson. We provide the most updated values of the mixing phases and discuss the importance of including the penguin contributions in their studies. Exploring intriguing patterns in purely tree decays, interesting new methodologies can be developed and applied. New data related to the CP asymmetries of key modes like $B^0_d \to \pi^0 K_S$ and $B^0_s \to K^+K^-$ lead to interesting results. The new $R_{K^{(*)}}$ measurement, compatible with the Standard Model, can still allow for electron-muon symmetry violation through new sources of CP violation.

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allows us to study these anomalies and search for hints of NP is discussed in Refs. [14, 15]. Let us summarise the key points of this methodology.

As a first step, we explore CP violation. Due to B^0_q–$\bar{B}^0_q$ mixing, interference effects arise between the $\bar{B}^0_s \to D^+_s K^-$ and $B^0_s \to D^+_s K^-$ channels. These interference effects lead to a time-dependent CP asymmetry, which yields the observables C, S, $\mathcal{A}_{\Delta\Gamma}$ and their CP conjugates. A measure of the strength of the interference effects is given by the quantities ξ and $\bar\xi$. Therefore, one can use the observables C, S, $\mathcal{A}_{\Delta\Gamma}$ and $\bar{C}$, $\bar{S}$, $\bar{\mathcal{A}}_{\Delta\Gamma}$, in order to determine ξ and $\bar\xi$, respectively, from the experimental data in an unambiguous way. Within the SM, in the product $\xi \times \bar\xi$ hadronic matrix elements cancel out allowing a theoretically clean extraction to $(\phi_s + \gamma)$. In the presence of NP, the generalisation of this relation takes the following form:

$$\xi \times \bar\xi = \sqrt{1 - 2\left[\frac{C + \bar{C}}{(1 + C)\,(1 + \bar{C})}\right]}\, e^{-i[2(\phi_s + \gamma_{\rm eff})]}, \tag{6}$$

where again hadronic uncertainties cancel. In particular, here it is possible that $C + \bar{C}$ is not equal to 0, as in the SM. The above expression leads to a theoretically clean determination of the angle:

$$\gamma_{\rm eff} \equiv \gamma + \gamma_{\rm NP}, \tag{7}$$

where $\gamma_{\rm NP}$ is a function of the NP parameters ρ, φ, δ, and $\bar\rho$, $\bar\varphi$, $\bar\delta$ (for the CP conjugate case). Here, $\rho = \left[A(\bar{B}^0_s \to D^+_s K^-)_{\rm NP}/A(\bar{B}^0_s \to D^+_s K^-)_{\rm SM}\right]$ measures the strength of NP, while δ and φ denote the CP-conserving and CP-violating phases, and similarly for $\bar\rho$, $\bar\varphi$, $\bar\delta$. Using information on γ [16] from other processes, we extract $\gamma_{\rm NP}$.

The second step corresponds to information from the branching ratios. We create ratios by combining the branching fractions of the non-leptonic decays we study with differential branching ratios of their semi-leptonic partner channels. These ratios with the semileptonic decays minimize the dependence on the CKM matrix elements and the hadronic form factors. Therefore, they provide a useful setup which permits the extraction of the colour factors $|a_1|$ from the data in the theoretically cleanest possible manner. Comparing these experimental results with theoretical predictions, we find tensions even up to the 4.8 σ level. This intriguing pattern is in line with what we expect from the puzzling situation with γ. In order to interpret these $|a_1|$ deviations, we introduce the quantities:

$$\bar{b} \equiv \frac{\langle \mathcal{B}(\bar{B}^0_s \to D^+_s K^-)_{\rm th}\rangle}{\mathcal{B}(\bar{B}^0_s \to D^+_s K^-)^{\rm SM}_{\rm th}} = 1 + 2\,\bar\rho\cos\bar\delta\cos\bar\varphi + \bar\rho^2, \tag{8}$$

$$b \equiv \frac{\langle \mathcal{B}(B^0_s \to D^-_s K^+)_{\rm th}\rangle}{\mathcal{B}(B^0_s \to D^-_s K^+)^{\rm SM}_{\rm th}} = 1 + 2\,\rho\cos\delta\cos\varphi + \rho^2, \tag{9}$$

where now we use as input the theoretical expectation of $|a_1|$. The extracted values of b and $\bar{b}$ deviate from the SM. We highlight that making use of other control channels, we are able to constrain the contributions from exchange diagrams and no anomalous enhancement is observed due to these topologies.

Last but not least, we explore how much room there is for NP utilising all three $\gamma_{\rm eff}$, b and $\bar{b}$. More specifically, we obtain correlations between the NP parameters $\rho(\varphi)$ and $\bar\rho(\bar\varphi)$, assuming that the strong phases equal to 0. Constraining these NP parameters, we find that it is possible to accommodate the current data with new contributions of moderate size.

The symmetry approach to quark and lepton masses and mixing

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Abstract

The Standard Model lacks an organizing principle to describe quark and lepton "flavours". We review the impact of neutrino oscillation experiments, which show that leptons mix very differently from quarks, placing a major challenge, but also providing a key input to the flavour puzzle. We briefly sketch the seesaw and "scotogenic" approaches to neutrino mass, the latter including also WIMP dark matter. We discuss the limitations of popular neutrino mixing patterns and examine the possibility that they arise from symmetry, giving a bottom-up approach to residual flavour and CP symmetries. We show how family and/or CP symmetries can generate novel viable and predictive mixing patterns. We review the model-independent ways to predict lepton mixing and test both mixing predictions as well as mass sum rules. We also discuss UV-complete flavour theories in four and more space-time dimensions, and their predictions. Benchmarks given include an A_4 scotogenic construction with trimaximal mixing pattern TM2. Higher-dimensional completions are also reviewed, such as 5-D warped flavordynamics. We present a T' warped flavordynamics theory with TM1 mixing pattern, detectable neutrinoless double beta decay rates and providing a very good fit of flavour observables, including quarks. We also review how 6-D orbifolds offer a way to determine the structure of the 4-D family symmetry from the symmetries between the extra-D branes. We describe a scotogenic A_4 orbifold predicting the "golden" quark-lepton mass relation, large neutrino mass with normal ordering, higher atmospheric octant, restricted reactor angle, and an excellent global flavour fit, including quark observables. Finally, we discuss promising recent progress in tackling the flavor issue through the use of modular symmetries.

Keywords: Fermion mixing, CP violation, generalized CP, flavor and modular symmetry, orbifolds, warped-flavordynamics.

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Resolving the Ultracollinear Paradox with Effective Field Theory

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Abstract

Naive intuition about scale decoupling breaks down in the presence of fermion masses. Kinematic enhancements can greatly extend the range where one needs to keep a finite mass in calculations to obtain a correct result at even the $\mathcal{O}(1)$ level. Treating a light fermion as massive though, leads to a known but somewhat obscure paradox, a seeming leading-order sensitivity to an arbitrarily small mass. We show how a proper formulation in effective field theory not only resolves the physical conundrum, but answers the very practical question of when fermion masses are required. This has important implications for the development of shower Monte Carlo above the weak scale.

1 Introduction

Mathematically, the fact that $\int_0^\infty \frac{m^2}{(k^2+m^2)^2} dk^2 = 1$ is utterly unremarkable. The physicist can recognize in this equation though, the seeds of catastrophe, even paradox. The integrand resembles a fermion propagator squared, with the numerator projected onto the terms from the "m" piece of $\not{p} + m$. The integration arises easily enough from loop momenta or phase space. Standard lore tells us to drop the masses of any fermions that are well below the energy scale of interest, unless one cares about the details of small power corrections. However, this simple integral reveals a strong discrepancy between zeroing out m before or after the calculation in question.

This noncommutation of integration and the limit $m \to 0$ was recognized long ago by Smilga and dubbed a "quasiparadox" of massless QED [1]. In fact, the issue plagues general theories of relativistic fermions. One can push to an absurd limit by imagining a particle with $m = 10^{-10^{10^{10}}}$ GeV. That would be significantly below current limits on the photon, and yet keeping the m piece of its propagator numerator seemingly leads to an unsuppressed perturbative contribution. By similar logic, one could imagine using the LHC to determine the Standard Model neutrino masses.

The physical resolution arises from thinking about the production of light fermions at high energies. In the immediate aftermath of the collision, the fermion is not in an approximately on-shell, asymptotic state (outside of a tiny corner of phase space). Instead, it begins life as a wavepacket that evolves in time, eventually decaying to the physical fermion plus a cloud of radiation. It is these emissions of other particles that introduce terms of the form $\frac{m^2}{(k^2+m^2)^2}$. Thus, if we want to experimentally determine the mass then we must observe this radiation. Sensitivity to the enhanced part of the integrand $\frac{m^2}{(k^2+m^2)^2}$, where the mass effects are important, requires $k_\perp^2 \lesssim m^2$. As we will detail in calculations below, what enters the denominators in our calculations of interest provides a condition on transverse momentum. However, as Smilga points out, generating such "ultracollinear" radiation takes time, and for a particle with energy E and flight path of length L, there is a lower cutoff on the emission angle of $\theta \sim 1/\sqrt{E\,L}$. We therefore pick up a contribution

$$\int_{k_{\perp\min}} \frac{m^2}{(k_\perp^2+m^2)^2} dk_\perp^2 \sim \frac{m^2}{E^2\theta^2} \sim \frac{m^2\,L}{E}, \tag{1}$$

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Bare mass effects on the reheating process after inflation

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We consider the effects of a bare mass term for the inflaton, when the inflationary potential takes the form $V(\phi) = \lambda\phi^k$ about its minimum with $k \geq 4$. We concentrate on $k = 4$, but discuss general cases as well. Further, we assume $\lambda\phi_{\rm end}^2 \gg m_\phi^2$, where $\phi_{\rm end}$ is the inflaton field value when the inflationary expansion ends. We show that the presence of a mass term (which may be present due to radiative corrections or supersymmetry breaking) can significantly alter the reheating process, as the equation of state of the inflaton condensate changes from $w_\phi = \frac{1}{3}$ to $w_\phi = 0$ when $\lambda\phi^2$ drops below m_ϕ^2. We show that for a mass $m_\phi \gtrsim T_{\rm RH}/250$, the mass term will dominate at reheating. We compute the effects on the reheating temperature for cases where reheating is due to inflaton decay (to fermions, scalars, or vectors) or to inflaton scattering (to scalars or vectors). For scattering to scalars and in the absence of a decay, we derive a strong upper limit to the inflaton bare mass $m_\phi < 350\ {\rm MeV}(T_{\rm RH}/10^{10}\ {\rm GeV})^{3/5}$, as there is always a residual inflaton background which acts as cold dark matter. We also consider the effect of the bare mass term on the fragmentation of the inflaton condensate.

I. INTRODUCTION

The hypothesis of a violent inflationary phase during the first moments of the Universe makes it possible to address several cosmological issues, ranging from the flatness of the Universe to the horizon or entropy problem [1]. However, a complete inflationary model requires above all a mechanism for a graceful exit. Indeed, the prolonged period of exponential expansion must end with a sufficiently efficient transfer of the oscillation modes of the inflaton condensate ϕ to a thermal bath [2, 3], i.e. reheating, that ensures a temperature $\gtrsim 2$ MeV to allow for standard big bang nucleosynthesis. Moreover, the density fluctuation spectrum produced during inflation should agree with observations of the CMB anisotropy spectrum [4], which in turn constrains the parameters of the inflaton potential $V(\phi)$.

The process of transferring the energy stored in inflaton oscillations to Standard Model particles is not instantaneous [5–8]. Rather, in many models, an oscillating inflaton condensate decays or scatters progressively producing a bath of relativistic particles. The efficiency of the reheating process depends on the rate of the energy transfer as well as on the shape of the inflaton potential, $V(\phi)$, about its minimum [9, 10]. Even if the exact shape of the potential at the end of inflation is unknown it can often be approximated about its minimum by a polynomial function of ϕ.

In many models of inflation, the inflaton potential can be approximated about its minimum by a quadratic term, $V(\phi) = \frac{1}{2}m_\phi^2\phi^2$. The Starobinsky model [11] is one example. In this case, only one Fourier mode of the inflaton oscillation contributes to the reheating process. The energy density in radiation, ρ_R, grows rapidly at first, and redshifts as $\rho_{\rm R} \propto a^{-\frac{3}{2}}$ where a is the cosmological scale factor, as decays continue to add to the radiation bath. Because $\rho_\phi \propto a^{-3}$, eventually, the radiation bath comes to dominate the total energy density, at which time we can define a reheating temperature. This occurs when the cosmological scale factor, $a_{\rm RH}$ satisfies $\rho_{\rm R}(a_{\rm RH}) = \rho_\phi(a_{\rm RH})$. This occurs (up to a numerical factor) when $H(a_{\rm RH}) \simeq \Gamma_\phi$, or $T_{\rm RH} \simeq \sqrt{\Gamma_\phi M_P}$, where H is the Hubble parameter, Γ_ϕ is the width of the inflaton condensate, and $M_P = 1/\sqrt{8\pi G_N} \simeq 2.4 \times 10^{18}$ GeV is the reduced Planck mass.

For a potential whose expansion about its minimum is $V(\phi) = \lambda\phi^k$, with $k \geq 4$, the exercise is more subtle, and requires a more involved analysis [9, 10]. The reheating process will in general depend on the spin of the final state particles in either inflaton decays or scatterings. In fact, in some cases reheating does not occur. For example, for $k = 4$, the evolution of $\rho_\phi \propto a^{-4}$ is the same as the evolution of $\rho_{\rm R} \propto a^{-4}$ for inflaton decays or scatterings to vector bosons [12], precluding the condition $\rho_\phi(a_{\rm RH}) = \rho_R(a_{\rm RH})$ to occur. However, we cannot exclude the presence of a bare mass term $\frac{1}{2}m_\phi^2\phi^2$, which may be subdominant at the end of inflation, and during

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Exploring the sensitivity to non-standard and generalized neutrino interactions through coherent elastic neutrino-nucleus scattering with a NaI detector

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After the first observation of coherent elastic neutrino-nucleus scattering (CEνNS) by the COHERENT collaboration, many efforts are being made to improve the measurement of this process, making it possible to constrain new physics in the neutrino sector. In this paper, we study the sensitivity to non-standard interactions (NSIs) and generalized neutrino interactions (GNIs) of a NaI detector with characteristics similar to the one that is currently being deployed at the Spallation Neutron Source at Oak Ridge National Laboratory. We show that such a detector, whose target nuclei have significantly different proton to neutron ratios (at variance with the current CsI detector), could help to partially break the parameter degeneracies arising from the interference between the Standard Model and NSI contributions to the CEνNS cross section, as well as between different NSI parameters. By contrast, only a slight improvement over the current CsI constraints is expected for parameters that do not interfere with the SM contribution. We find that a significant reduction of the background level would make the NaI detector considered in this paper very efficient at breaking degeneracies among NSI parameters.

I. INTRODUCTION

Coherent elastic neutrino-nucleus scattering (CEνNS) [1] is a privileged process to probe new physics in the neutrino sector. So far, the only measurements of CEνNS have been done at the Spallation Neutron Source (SNS) at Oak Ridge National Laboratory, USA, by the COHERENT collaboration. The first observation of this process was performed with a CsI detector [2, 3]. Another detector, with liquid Argon as a target, was subsequently used by the COHERENT collaboration [4].

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Froggatt-Nielsen Meets the SMEFT

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Abstract

We study the matching of Froggatt-Nielsen theories of flavour onto the Standard Model Effective Field Theory (SMEFT), upon integrating out a heavy Beyond-the-Standard-Model (BSM) scalar 'flavon' whose vacuum expectation value breaks an Abelian flavour symmetry at energies $\Lambda_{\rm FN}$ well above the electroweak scale, $\Lambda_{\rm FN} > \Lambda_{\rm SM}$. We include matching contributions to the infrared $d_{\rm SM} = 6$ (Warsaw basis) SMEFT sourced from ultraviolet contact terms suppressed up to order $1/\Lambda_{\rm UV}^2$ in the Froggatt-Nielsen Lagrangian, where $\Lambda_{\rm UV} > \Lambda_{\rm FN}$ is an arbitrary deep-ultraviolet scale where further unspecified BSM particles are dynamical. This includes tree-level (one-loop) ultraviolet diagrams with $d_{\rm FN} = 6$ (5) effective vertices. We first do so with a toy model, but then generalize our findings to arbitrary Frogatt-Nielsen charges. Our results indicate a rich and non-trivial signature of Froggatt-Nielsen theories on the (otherwise) model-independent operators of the SMEFT, and we briefly speculate on extending our analysis to broader classes of BSM flavour models, e.g. non-Abelian and/or gauged theories. We thus take an important step towards determining how to use rapidly developing theoretical and experimental SMEFT technologies to gain unambiguous insight into the SM's longstanding fermion flavour puzzle.