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Cutting-Edge Tools for Cutting Edges

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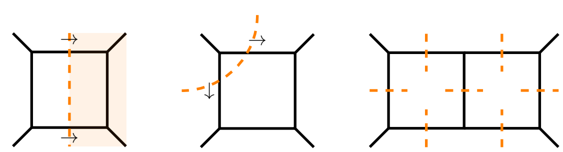
We review different notions of cuts appearing throughout the literature on scattering amplitudes. Despite similar names, such as *unitarity cuts* or *generalized cuts*, they often represent distinct computations and distinct physics. We consolidate this knowledge, summarize how cuts are used in various computational strategies, and explain their relations to other quantities including imaginary parts, discontinuities, and monodromies. Differences and nuances are illustrated on explicit examples.

CONTENTS

I. INTRODUCTION

At the heart of modern research into scattering amplitudes are *cuts*. Diagrammatically, cutting a diagram means tagging a subset of its internal edges, here denoted with dashed lines, e.g.



(1)

However, this operation can have distinct meanings depending on the physical or mathematical context in which it is employed. The purpose of this article is to review different flavors of cuts appearing in the literature, as well as explain how they are used in physical applications and as a computational scheme.

While details differ depending on the application, cuts always come with a notion of placing particles with momentum p and mass m on their mass shell, i.e., $p^2 = m^2$, which can be implemented as a Dirac delta function or a residue prescription. As a result, in perturbation theory the loop integrand simplifies and the number of loop integrations drops, which is ultimately why cuts become a useful tool. Here, we will categorize cuts by their purpose. Broadly, they are employed to compute:

- **Imaginary parts and total discontinuities.** Historically the oldest version, which is codified by the *Cutkosky rules* and directly descends from unitarity. Unitarity cuts appear as a consequence of integrating over the phase-space of on-shell states and become useful for computing cross sections through the optical

Testing gravitational waveforms in full General Relativity

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We perform a comprehensive analysis of state-of-the-art waveform models, focusing on their predictions concerning kick velocity and inferred gravitational wave memory. In our investigation we assess the accuracy of waveform models using energy-momentum balance laws, which were derived in the framework of full, non-linear General Relativity. The numerical accuracy assessment is performed for precessing as well as non-precessing scenarios for models belonging to the *EOB*, *Phenom*, and *Surrogate* families. We analyze the deviations of these models from each other and from Numerical Relativity waveforms. Our analysis reveals statistically significant deviations, which we trace back to inaccuracies in modelling subdominant modes and inherent systematic errors in the chosen models. We corroborate our findings through analytical considerations regarding the mixing of harmonic modes in the computed kick velocities and inferred memories.

I. INTRODUCTION

The first direct detection of gravitational waves (GWs) from the merger of two black holes in 2015 [1] marked a milestone in the field of astrophysics, confirming a key prediction of Einstein's General Theory of Relativity (GR) and ushering in a new era of observational astronomy. The waveforms matched against the GW signal encode a wealth of information, including the masses and spins of the binaries, the distances to the sources, and the geometry of their motion. By analyzing these waveforms, astrophysicists can uncover the underlying physical processes, discern the properties of exotic objects, and validate theoretical models with unprecedented precision.

To date, the process of parameter estimation and the testing of GR necessitate numerical modeling of gravitational waveforms across a wide range of source parameters, including masses, spins, and other relevant factors pertaining to the merging objects. These modelled waveforms are used as fitting templates with respect to actual data. The effectiveness of this template-to-signal match hinges on the precision of the estimated waveforms. Therefore, in order to extract meaningful information from signals, it is crucial to construct comprehensive and accurate waveform templates that faithfully capture the physics of GR. This requirement is further substantiated by the expected increase in signal-to-noise-ratio of future GW observatories such as LISA [2], the Einstein Telescope [3], and the Cosmic Explorer [4]. Their increased resolution and sensitivity opens them up to more subtle effects like the gravitational memory [5–10] and they may even reveal physics beyond GR [11].

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However, deviations between templates and the actual waveforms contained in the observational data introduce systematic biases, compromising the reliability of the information extracted from the signal. To counteract such biases, a diverse set of template waveforms is employed when analyzing data from GW instruments. Among these template waveforms, the ones obtained from Numerical Relativity (NR) simulations are the most reliable. Their disadvantage, however, is their consumption of vast amounts of computational resources for each simulation, i.e., for each choice of parameters describing an individual merging scenario. This time-consuming and resource-intense process poses a significant challenge, particularly as the volume of data to be processed is expected to increase drastically in the upcoming years with the advent of multiple ground- and space-based instruments like LISA [12] and LIGO/Virgo [13, 14]. Furthermore, as the measuring precision advances, deviations from GR [11] may reveal themselves in the observed data. Detecting such deviations necessitates an expanded parameter space to account for alternative descriptions of gravity, which consequently amplifies the number of waveforms against which the data must be tested.

To address these challenges, and in particular to tackle the efficiency issue of the waveform generation process, multiple alternatives to NR simulations were established. Prominent representatives of alternative waveform models are the *Surrogate* models [15–17], phenomenological models [18–21] and effective-one-body simulations [22–27]. To obtain reliable results within reasonable timescales, the models adopt distinct strategies to compute the gravitational strain. Each model focuses on different physical aspects of compact binary coalescence and is capable of producing a waveform within certain parameter ranges in an efficient manner. To understand what distinguishes the different approximant families, it is helpful to divide the compact binary coalescence into three phases: the inspiral, the merger, and the ringdown phase. The objective of each approximant family is to generate waveforms that replicate NR without re-

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Trans-series from condensates

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Abstract: The Shifman–Vainshtein–Zakharov (SVZ) sum rules provide a method to obtain trans-series expansions in many quantum field theories, in which exponentially small corrections are calculated by combining the operator product expansion with the assumption of vacuum condensates. In some solvable models, exact expressions for trans-series can be obtained from non-perturbative results, and this makes it possible to test the SVZ method by comparing its predictions to these exact trans-series. In this paper we perform such a precision test in the example of the fermion self-energy in the Gross–Neveu model. Its exact trans-series expansion can be extracted from the large N solution, at the first non-trivial order in $1/N$. It is given by an infinite series of exponentially small corrections involving factorially divergent power series in the 't Hooft parameter. We show that the first two corrections are associated to two-quark and four-quark condensates, and we reproduce the corresponding power series exactly, and at all loops, by using the SVZ method. In addition, the numerical values of the condensates can be extracted from the exact result, up to order $1/N$.

Infinite Order Hydrodynamics: an Analytical Example

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We construct a kinetic model for matter-radiation interactions where the hydrodynamic gradient expansion can be computed analytically up to infinite order in derivatives, in the fully non-linear regime, and for arbitrary flows. The frequency dependence of the opacity of matter is chosen to mimic the relaxation time of a self-interacting scalar field. In this way, the transient sector simulates that of a realistic quantum field theory. As expected, the gradient series is divergent for most flows. We identify the mechanism at the origin of the divergence, and we provide a successful regularization scheme. Additionally, we propose a universal qualitative framework for predicting the breakdown of the gradient expansion of an arbitrary microscopic system undergoing a given flow. This framework correctly predicts the factorial divergence of the gradient expansion in most non-linear flows and its breakdown due to stochastic fluctuations. It also predicts that jets may induce an ultraviolet divergence in the gradient expansion of quark matter hydrodynamics.

Introduction - The most pressing open question in relativistic fluid mechanics is: "How far can we push hydrodynamics before it breaks down?" [1–20]

Let us make this question precise. The Knudsen number $\mathrm{Kn} = \lambda/L$ is the ratio between the particles' mean free path λ (defining the microscopic scale) and the characteristic length scale L of the flow of interest [21, 22]. It is common knowledge [23] that, if $\mathrm{Kn} \to 0$, we can model the system as an ideal fluid, while when $\mathrm{Kn} \gtrsim 1$, we need to rely on microphysics. Thus, there is some value of $\mathrm{Kn} \in (0, 1]$ at which hydrodynamics stops working. Can we identify it precisely?

The answer depends on which hydrodynamic theory one is using. The ideal fluid breaks down at any finite value of Kn, since it is non-dissipative, and it predicts that waves survive forever. These issues are fixed in Navier-Stokes theory, whose breakdown is conventionally set at $\mathrm{Kn} = 0.1$ [24]. However, one may try to do even better. Most derivations of hydrodynamics from kinetic theory [25, 26] and holography [27, 28] express the stress-energy tensor $T^{\mu\nu}$ of a fluid as a formal power series in Kn, known as the "gradient expansion" [29],

$$T^{\mu\nu}(\mathrm{Kn}) = T^{\mu\nu}_{\mathrm{ID}} + T^{\mu\nu}_1 \mathrm{Kn} + T^{\mu\nu}_2 \mathrm{Kn}^2 + \dots , \qquad (1)$$

where the zeroth order is the ideal fluid, the first order is Navier-Stokes, the second order is the Burnett equation [30], and higher orders correspond to fluid theories with higher derivative corrections. One hopes that, by adding more and more powers of Kn, the regime of applicability of hydrodynamics will expand more and more, increasing the accuracy of hydrodynamics for all Kn up to the radius of convergence $\mathrm{Kn}^\star$ of the series (1). Following this line of thought, it would then be natural to conclude that such radius $\mathrm{Kn}^\star$ is what ultimately marks the rigorous breakdown of hydrodynamics [31].

Unfortunately, reality turns out to be more complicated. First, there are indications that, in most realistic scenarios, $\mathrm{Kn}^\star = 0$ [10, 13, 32]. This means that, if we keep adding higher and higher orders in Kn, at some point the region of applicability of (1) shrinks instead of expanding. Secondly, equation (1) makes sense only if the function $T^{\mu\nu}(\mathrm{Kn})$ is analytic in Kn. In principle, there may be non-smooth corrections like $\mathrm{Kn}^{3/2}$ [33], or non-perturbative corrections like $e^{-1/\mathrm{Kn}}$ [34]. Therefore, the breakdown scale of hydrodynamics remains unknown.

The dream of any fluid theorist would be to have a microscopic model where $T^{\mu\nu}(\mathrm{Kn})$ can be computed exactly for arbitrary flow, at arbitrary Kn, in the fully non-linear regime, and where all the terms $T^{\mu\nu}_n$ in the series (1) have exact analytical formulas. Such model should have realistic interactions, to ensure that the dependence of $T^{\mu\nu}$ on Kn mimics the behavior of some microscopic quantum field theory. Finally, one should be able to extract from it general lessons about the expansion (1). In this Letter, we provide a model that fulfills all these requirements.

Notation: We work in Minkowski space, with signature $(-,+,+,+)$, and adopt natural units: $c = \hbar = k_B = 1$.

The kinetic model - Our model setup is a radiation-hydrodynamic system [35–41], namely a fluid mixture comprised of two substances: a material medium M with negligibly short mean free path (i.e. $\mathrm{Kn}_M \equiv 0$), and a diluted radiation gas R with a finite, possibly large, mean free path (i.e. $\mathrm{Kn}_R > 0$) [42, 43]. The former is modeled as an ideal fluid, with a well-defined temperature $T(x^\alpha)$ and flow velocity $u^\mu(x^\alpha)$. The latter can exist in far-from-equilibrium states, and we must track its kinetic distribution function $f_p(x^\alpha)$ [44, 45] ($p =$ momentum). The total stress-energy tensor is the sum of a material non-viscous part and a radiation part:

$$T^{\mu\nu} = T^{\mu\nu}_M + \int \frac{d^3p}{(2\pi)^3 p^0} f_p \, p^\mu p^\nu . \qquad (2)$$

The radiation particles do not interact with each other, but are randomly absorbed and emitted by the medium (neglecting scattering). Thus, the Boltzmann equation is of relaxation type [35, 46]. Taking the relaxation time to be $\tau_p = -u_\mu p^\mu / g$ (with $g > 0 = \text{constant}$), we have

$$p^\mu \partial_\mu f_p = -u_\mu p^\mu \, \frac{f^{\mathrm{eq}}_p - f_p}{\tau_p} = g \, (f^{\mathrm{eq}}_p - f_p) . \qquad (3)$$

Since τ_p grows linearly with $-u_\mu p^\mu$, our medium is opaque at low frequencies, and transparent at high frequencies [35]. The function f^{eq}_p is the value that f_p would

Viscoelastic response and anisotropic hydrodynamics in Weyl semimetals

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We study viscoelastic response in Weyl semimetals with broken time-reversal symmetry. Topology and anisotropy of the Fermi surface are manifested in the viscoelasticity tensor of the electron fluid. In the dynamic (inter-band) part of this tensor, the anisotropy leads to a qualitatively different, compared to isotropic models, scaling with frequency and the Fermi energy. While components of the viscosity tensor determined by the Fermi surface properties agree in the Kubo and kinetic formalisms, the latter misses the anomalous Hall viscosity determined by filled states below the Fermi surface. The anisotropy of the dispersion relation is also manifested in the acceleration and relaxation terms of the hydrodynamic equations.

I. INTRODUCTION

Experimental discovery of hydrodynamic transport in graphene [1–9] reignited the interest to electron hydrodynamics first observed in GaAs heterostructures [10, 11]. This is particularly fascinating since the foundation of electron hydrodynamics was laid down in the 1960s in the seminal works of R. Gurzhi [12, 13]. Being an interesting regime with strong electron-electron interactions, electron hydrodynamics has several manifestations including the Gurzhi effect [12], Poiseuille profile of electric current, formation of vortices of electron fluid, etc.; see Refs. [14–16] for a review.

A characteristic and very important property of any fluid is its viscosity. Viscosity is a rank-4 tensor that relates the fluid stress to coordinate derivatives of the fluid velocity. In continuum mechanics, the viscoelastic stress tensor combines the response to strain (elasticity) and the time derivative of strain (viscosity); in what follows, we will use viscoelastic and viscous tensors interchangeably. In systems with rotational invariance, such as most fluids, the structure of the shear viscosity tensor is fixed by symmetry, and viscous response is determined only by two coefficients [17]: bulk and shear viscosities. However, solid-state materials are rarely isotropic where the rotational symmetry is commonly reduced only to certain angles of rotation.

Manifestations of anisotropy of the band dispersion in electron hydrodynamics were considered in Refs. [18–25]. In anisotropic metals, the reduced symmetry can lead to unusual viscosity tensors with additional components. Using a lattice regularization proposed in Ref. [19], the nondissipative Hall viscosity was analyzed in [26], however, other components of the viscosity tensor and the dynamic viscosity received less attention.

In addition to the anisotropy of the band dispersion, certain materials allow for the nontrivial topology of their electron wave functions. Topological aspects of viscoelastic response were addressed in Refs. [19, 20, 23, 24, 27–32]. The main attention, however, was paid to nondissipative or Hall responses [19, 26, 33–35] in mainly 2D systems. Three-dimensional (3D) topological materials exemplified by Weyl semimetals may also demonstrate nontrivial hydrodynamic response related to their topology [36–43]; experimental signatures of the hydrodynamic behavior in the Weyl semimetal WP_2 were reported in Ref. [44]. As an example of the topology manifestation in the viscoelasticity tensor in time-reversal symmetry (TRS) broken Weyl materials, we mention the anomalous Hall viscosity determined by the separation of the Weyl nodes in the Brillouin zone [29]. However, the calculation of the complete viscoelastic response that goes beyond the anomalous Hall viscosity, includes both dissipative and nondissipative parts, and accounts for the Weyl node topology in 3D Weyl semimetals is still lacking.

In this paper, we fill this gap and calculate the viscoelastic response of TRS-broken Weyl semimetals. One of our main findings is that the separation of the Weyl nodes in the Brillouin zone is manifested in both nondissipative (i.e., anomalous Hall) and dissipative components of the viscoelasticity tensor. Using the Kubo framework [45], we calculate both static and dynamic viscoelastic responses in linearized and two-band models of Weyl semimetals. In our calculations, we use two formulations of the stress tensor, which plays the key role in the Kubo approach: the canonical stress tensor, which follows from the coupling to mechanical strains [28, 29], and the Belinfante-like tensor, which includes contributions connected with the internal angular momentum [19, 30] and arises due to coupling to the background geometry [19]. These approaches were recently used also in Ref. [24] for chiral magnetic materials, which realize the

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Fast neutrino flavor conversions in a supernova: emergence, evolution, and effects

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Fast flavor conversions (FFCs) of neutrinos, which can occur in core-collapse supernovae (CCSNe), are multiangle effects. They depend on the angular distribution of the neutrino's electron lepton number (ELN). In this work, we present a comprehensive study of the FFCs by solving the multi-energy and multiangle quantum kinetic equations with an extended set of collisional weak processes based on a static and spherically symmetric CCSN matter background profile. We investigate the emergence and evolution of FFCs in models featuring different ELN angular distributions, considering scenarios with two and three neutrino flavors. The spectrogram method is utilized to illustrate the small-scale spatial structure, and we show that this structure of neutrino flavor coherence and number densities in the nonlinear regime is qualitatively consistent with the dispersion relation analysis. On the coarse-grained level, we find that different asymptotic states can be achieved following the FFCs depending on the locations and shapes of the ELN distributions, despite sharing a common feature of the elimination of the ELN angular crossing. While equilibration among different neutrino flavors may be achieved immediately after the prompt FFCs, it is not a general outcome of the asymptotic state, as subsequent feedback effects from collisional neutrino-matter interactions come into play, particularly for cases where FFCs occur inside the neutrinosphere. The impacts of FFCs and the feedback effect on the net neutrino heating rates, the equilibrium electron fraction of CCSN matter, and the free-streaming neutrino energy spectra are quantitatively assessed. Other aspects including the impact of the vacuum term and the coexistence with other type of flavor instabilities are also discussed.

I. INTRODUCTION

Core-collapse supernovae (CCSNe) are cataclysmic events when massive stars reach the end of their lives. During the evolution of a CCSN, a nascent proto-neutron star (PNS) forms at the center as a prolific source of neutrinos. These neutrinos play pivotal roles on the CCSN dynamics and the evolution of chemical composition. They interact with the medium through both charged- and neutral-current weak interactions in the proximity of the PNS and deposit energy, facilitating the shock revival via reheating of material in the post-shocked layer and leading to the eventual mass ejection. Particularly, the charged-current interactions determine the proton-to-baryon ratio, denoted by the electron fraction Y_e, which is a crucial quantity for the nucleosynthesis results of CCSN explosions. A better knowledge of the flux intensities and flavor content of neutrinos is necessary to robustly model the inner dynamics of CCSNe, to predict the elemental compositions in CCSN ejecta, and to determine the neutrino signals for the detection of the next galactic supernova event (see e.g., Refs. [1, 2] for recent reviews).

The flavor oscillations of neutrinos among ν_e, ν_μ, and ν_τ in vacuum and in medium have been well studied and confirmed by various ground-based neutrino experiments [3]. When neutrino fluxes are sufficiently high in CCSNe, the forward scattering among neutrinos themselves leads to various collective phenomena of flavor instability. Particularly the fast flavor conversion (FFC) associated with the fast flavor instability (FFI; see e.g., Refs. [4–7] for reviews) attracts great interest in recent years owing to the vastly rapid conversion rate within nanoseconds and over a distance shorter than a coin. Studies based on results from the multi-dimensional CCSN simulations have shown a general occurrence of FFIs in certain regions ahead of the shock wave, near the neutrinosphere, or even deep inside the PNS [8–17].

Since the first proposal of FFI in Ref. [18], the advance of both theory and methodology throughout the past decade has improved our understanding of FFCs and guided the line of research toward the ultimate goal of implementing neutrino oscillations in CCSNe. A generic framework governing the coherent flavor evolution and collisional neutrino-matter interactions is prescribed by the neutrino quantum kinetic equation (νQKE) [19–22]. The linear stability analysis (LSA) of the νQKE provides a powerful tool to diagnose the existence of flavor instabilities [23–26]. It has been proved based on the

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Bogoliubov phonons in a Bose-Einstein condensate from the one-loop perturbative renormalization group

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Wilson's renormalization-group approach to the weakly-interacting single-component Bose gas is discussed within the symmetry-broken, condensate phase. Extending upon the work by Bijlsma and Stoof [1], wave-function renormalization of the temporal derivative contributions to the effective action is included in order to capture sound-like quasiparticle excitations with wave lengths larger than the healing-length scale. By means of a suitable rescaling scheme we achieve convergence of the coupling flows, which serve as a means to determine the condensate depletion in accordance with Bogoliubov theory, as well as the interaction-induced shift of the critical temperature.

I. INTRODUCTION

Since the experimental realization of Bose-Einstein condensation in dilute interacting atomic gases [2, 3] there has been great interest in further exploring these systems both experimentally and theoretically. The basic theoretical approach is based on the Gross-Pitaevskii model, which, at the relevant low energies, describes the weak interparticle interactions within a contact-potential approximation. To capture the condensate phase and its fundamental excitations, Bogoliubov's ansatz builds on the assumption of a spontaneously broken U(1) symmetry and on an expansion about the field expectation value [4]. A subsequent truncation at Gaussian order represents an approximation, in which Bogoliubov-de Gennes diagonalization of the propagator yields the spectrum of quasiparticle excitations, which have collective, sound-wave character at long wavelengths. It allows determining leading-order perturbative corrections to thermodynamic observables such as the depletion of the condensate density and the associated shift of the chemical potential [5]. In three spatial dimensions, the approximation is valid in the dilute-gas regime, where the characteristic s-wave scattering length is much smaller than the interparticle spacing. Beyond this order of approximation, perturbation theory allows computing further corrections. At next-to-leading order, Beliaev's approximation involves all one-loop corrections to the Bogoliubov quasiparticle effective action [6–8]. See [9] for a review of related approaches to the weakly interacting Bose gas.

In the aforementioned perturbative extensions of the self-consistent framework, the sound-wave energy of excitations, linear in momentum k for $k \to 0$, typically gives rise to logarithmic infrared (IR) divergences in $d = 3$, which makes it difficult to apply self-consistent diagrammatic renormalization methods [10]. It was shown that these divergences cause the anomalous self-energy to vanish at zero momentum [11, 12], which implies that self-consistent higher-order approaches require the corresponding normal contribution to the zero-momentum self-energy to equal the chemical potential in order for the Hugenholtz-Pines or Goldstone theorem to be fulfilled and thus the dispersion to be gapless [13]. Different approaches have been explored to obtain, in this context, perturbative corrections, including self-consistent diagrammatic perturbation theory [11, 12, 14, 15], in density-phase representation [16], within a number-conserving perturbative approach [17, 18], or in a both, conserving and gapless Hartree-Fock-Bogoliubov approximation [19]. In the strong-coupling limit a resummation scheme of IR divergences has been presented in [20]. IR divergences can in general be handled by means of renormalization group (RG) theory [21–26]. Within the RG approach, one iteratively integrates out fluctuations starting from the ultraviolet (UV) end of the spectrum and reabsorbs their effect in redefined coupling constants. This is achieved by means of RG flow equations governing the couplings, which parametrize an effective description at a given maximum spatial resolution scale.

The weakly interacting Bose gas in $d = 3$ and thermal equilibrium has been extensively studied using RG methods [1, 27–50]: Near criticality, the interaction-induced shift in the critical temperature has been determined using flow equations in perturbative approximation [1, 28, 29], within a non-perturbative functional RG approach [30, 31], and in the high temperature limit [32–35, 51]. The results can be compared with those of numerical approaches [52–57]. Furthermore, RG treatments have served to obtain critical exponents such as the exponent ν governing the scaling of the correlation length near criticality. Thereby, different techniques and approximation methods were employed, including derivative expansions [36], Wilson's momentum-shell method [1], and expansions in powers of $\epsilon = 4 - d$ in d spatial dimensions [37], considering homogeneous as well as confined [28, 38, 39] systems. In [1], the critical exponent was determined as $\nu = 0.685$. Given that the thermal condensation phase transition of the interacting Bose gas belongs to the O(2) universality class, this value is to be compared with high-precision results from both theoretical and experimental studies. An expansion of anomalous dimensions up to six loops in perturbation theory in three spatial dimensions gave $\nu = 0.6703(15)$, while the ϵ-expansion, which avoids the problem of IR divergences, yields $\nu = 0.6680(35)$ [58]. Measuring the superfluid phase transi-

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Bosonic Dark Matter Dynamics in Hybrid Neutron Stars

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This research studies the intricate interplay between dark and baryonic matter within hybrid neutron stars enriched by anisotropic bosonic dark matter halos. Our modelling, guided by the equation of state with a free parameter, reveals diverse mass-radius correlations for these astronomical objects. A pivotal result is the influence of dark matter characteristics—whether condensed or dispersed—on the observable attributes of neutron stars based on their masses. Our investigation into anisotropic models, which offer a notably authentic representation of dark matter anisotropy, reveals a unique low-density core halo profile, distinguishing it from alternative approaches. Insights gleaned from galactic clusters have further refined our understanding of the bosonic dark matter paradigm. Observational constraints derived from the dynamics of galaxy clusters have been fundamental in defining the dark matter particle mass to lie between 0.05 GeV and 0.5 GeV and the scattering length to range from 0.9 fm to 3 fm. Using terrestrial Bose-Einstein condensate experiments, we have narrowed down the properties of bosonic dark matter, especially in the often overlooked 3 to 30 GeV mass range. Our findings fortify the understanding of dark and baryonic matter synergies in hybrid neutron stars, establishing a robust foundation for future astrophysical pursuits.

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I. INTRODUCTION

Dark matter, one of the most intriguing and mysterious phenomena in astrophysics, remains a subject of ongoing investigation [e.g., 1, 2]. This invisible form of matter, which does not emit, absorb, or reflect electromagnetic radiation, accounts for roughly 27% of the Universe's total mass-energy content [e.g., 3]. The presence of dark matter has been deduced from its gravitational influence on galaxy movements, the vast cosmic structures, and the cosmic microwave background radiation [e.g., 4].

It is widely accepted that dark matter cannot be composed of fundamental particles within the Standard Model of particle physics, and it is more likely that dark matter is made up of particles that have not yet been discovered. Various hypothetical particle candidates have been proposed as potential solutions to the dark matter problem, and these particles can generally be classified into several categories based on their mass [5–8]. These categories include fuzzy dark matter or axion-like particles, axions, sterile neutrinos, and weakly interacting massive particles (WIMPs).

Our focus in this work is to investigate how the structure of neutron stars can be affected by dark matter particles within the WIMPs and axion mass ranges. In particular, we will be focusing on particles in the $10^{-2} - 10^{2}$ GeV range.

There are several papers in the literature that discuss the relationship between dark matter and neutron stars. Some recent examples include [9, 10], which focus on general self-annihilating WIMP models; [11–21], which focus on specific fermionic dark matter models; [22, 23], that consider Bose-Einstein Condensate (BEC) dark matter; and [24] where both fermionic and BEC models are studied. These papers explore the possible effects of dark matter on neutron star properties and the potential for dark matter detection through observations of neutron stars. Additionally, there are several reviews that provide a more comprehensive overview of the field, such as Lattimer [25] and Del Popolo et al. [26].

Anisotropic matter exhibits different properties or behaviours depending on the direction [for a review see 27, 28]. Such behaviour can lead to pressure differences in various directions within neutron stars or other astronomical objects [e.g., 29–31]. This characteristic influences how matter interacts with surrounding objects, affecting their formation, structure, and evolution, shaping our understanding of dark matter. For instance, dark matter clouds are expected to exhibit local anisotropy, similar to any collisionless system of particles. Researchers have extensively studied these systems, especially in the context of galaxy dynamics [e.g., 32–34].

The theory of anisotropic fluids in General Relativity is well-established. Past research has demonstrated that anisotropic fluids could be geodesic in general relativity [35]. A comprehensive study of spherically symmetric dissipative anisotropic fluids has been presented, and exact static spherically symmetric anisotropic solutions of field equations have been obtained and analyzed by Herrera et al. [36], Bayin [37], and Herrera et al. [38]. Furthermore, calculations of anisotropic stars in general relativity and their mass-radius relations have been conducted Mak and Harko [39]. A detailed collection of

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Induced Gravitational Wave interpretation of PTA data: complete study for general equation of state

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We thoroughly study the induced gravitational wave interpretation of the possible gravitational wave background reported by PTA collaborations, considering the unknown equation of state w of the early universe. We perform a Bayesian analysis of the NANOGrav data using the publicly available PTArcade code together with SIGWfast for the numerical integration of the induced gravitational wave spectrum. We focus on two cases: a monochromatic and a log-normal primordial spectrum of fluctuations. For the log-normal spectrum, we show that, while the results are not very sensitive to w when the GW peak is close to the PTA window, radiation domination is out of the 2σ contours when only the infra-red power-law tail contributes. For the monochromatic spectrum, the 2σ bounds yield $0.1 \lesssim w \lesssim 0.9$ so that radiation domination is close to the central value. We also investigate the primordial black hole (PBH) counterpart using the peak formalism. We show that, in general terms, a larger width and stiffer equation of state alleviates the overproduction of PBHs. No PBH overproduction requires $w \gtrsim 0.42$ up to 2-σ level for the monochromatic spectrum. Furthermore, including bounds from the cosmic microwave background, we find in general that the mass range of the PBH counterpart is bounded by $10^{-5}M_\odot \lesssim M_{\rm PBH} \lesssim 10^{-1}M_\odot$. Lastly, we find that the PTA signal can explain the microlensing events reported by OGLE for $0.42 \lesssim w \lesssim 0.50$. Our work showcases a complete treatment of induced gravitational waves and primordial black holes for general w for future data analysis.

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Hadron-quark phase transition in the neutron star with vector MIT bag model and Korea-IBS-Daegu-SKKU functional

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Abstract

Employing the Korea-IBS-Daegu-SKKU (KIDS) density functional for the hadron phase and the MIT bag model with vector (vBag) model for the quark phase, we obtain hadron-quark phase transition in neutron stars considering Maxwell construction. The structural properties of the resultant hybrid stars are computed for three different values of bag constant (B) in the range $B^{1/4}$ =(145−160 MeV). We studied the effects of symmetry energy (J) on the hybrid star properties with the different KIDS model and found that J has important influence not only on the transition properties like the transition mass, transition radius and jump in density due to phase transition, but also on the stability of the hybrid stars. The vector repulsion of the quark phase via the parameter G_V has profound influence in obtaining reasonable hybrid star configurations, consistent with the recent astrophysical constraints on the structural properties of compact stars. Within the aforesaid range of B, the value of G_V is constrained to be $0.3 \lesssim G_V \lesssim 0.4$ in order to obtain reasonable hybrid star configurations.

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Weak Lensing Constraints on Dark Matter-Baryon Interactions with N-Body Simulations and Machine Learning

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We investigate the elastic scattering cross section between dark matter and protons using the DES Year 3 weak lensing data. This scattering induces a dark acoustic oscillation structure in the matter power spectra. To address non-linear effects at low redshift, we utilize principal component analysis alongside a limited set of N-body simulations, improving the reliability of our matter power spectrum prediction. We further perform a robust Markov Chain Monte Carlo analysis to derive the upper bounds on the DM-proton elastic scattering cross-section, assuming different velocity dependencies. Our results, presented as the first Frequentist upper limits, are compared with the ones obtained by Bayesian approach. Compared with the upper limits derived from the Planck cosmic microwave background data, our findings from DES Year 3 data exhibit improvements of up to a factor of five. In addition, we forecast the future sensitivities of the China Space Station Telescope, the upcoming capabilities of this telescope could improve the current limits by approximately one order of magnitude.

I. INTRODUCTION

Dark Matter (DM) is one of the most fundamental mysteries in modern physics, even though its gravitational effects are well understood. Besides gravity, the interactions between DM and baryons are also of great interest, as explored by experiments such as PandaX [1] and XENONnT [2]. However, no signal has been detected for DM masses above about 1 GeV. Therefore, the focus of experiments has shifted to the sub-GeV mass range, for example, CDEX [3], SENSEI [4], etc.

The interaction between DM and baryons can change the matter distribution in our universe, creating a dark acoustic oscillation (DAO) feature in the matter power spectra. DAO affects the Cosmic microwave background (CMB) anisotropies and the structure formation in the early universe, and constrains the DM-proton elastic scattering cross-section [5–8]. However, the DAO suppression, similar to that of warm DM, is more sensitive to small-scale observations. For velocity independent case, one obtains a stronger limit on this cross-section ($\sigma_{\chi p} < 2.8\times10^{-28}$ cm^3 s^{-1} for DM mass around 10 MeV) from the Milky Way satellite abundance [8–11], and the tightest limit ($\sigma_{\chi p} < 1.7\times10^{-29}$ cm^3 s^{-1} for DM mass around 10 MeV) from the Lyman-α-forest [8, 12, 13]. Nevertheless, the theoretical predictions of these small-scale observations are affected by the non-linear evolution of power spectra and the baryonic feedback. A recent research have explored such baryonic feedback in the galaxies affected by the DM-baryon interactions through hydrodynamical simulation [14]. However, the systematic uncertainties of these predictions remain unclear.

Weak Gravitational Lensing (WL) is a good tool for probing the late-time Large Scale Structure (LSS) of the universe. Through statistical analyses of shape distortions in numerous galaxies induced by foreground matter fields, it can directly map the LSS of the universe. We can mask the small-scale WL data to reduce the uncertainties associated with baryonic feedback, which are more pronounced in observations of the Lyman-α-forest at the small scales. In addition, WL data is expected to be more sensitive than the CMB anisotropies. Many recent and upcoming surveys, including Dark Energy Survey (DES) [15], Kilo-Degree Survey (KiDS) [16, 17], Subaru Hyper Suprime-Cam (HSC) [18, 19], Euclid [20], the Vera C. Rubin Observatory [21], the Nancy Grace Roman Space Telescope [22], the Wide Filed Survey Telescope (WFST) [23, 24], the Mephisto Telescope [25, 26] and China Space Station Telescope (CSST) [27–29], greatly improve our understanding of the matter distribution in the late universe. They, in turn, have the potential to reveal the fundamental physics of the interaction between DM and baryonic matter. In this work, we use the data from DES three-year (DES Y3) '`3×2pt`' WL observations along with the CMB and baryonic acoustic oscillation (BAO) observations data. Furthermore, we generate the mock data for CSST and present a forecast of the power of CSST.

Because the photometric galaxy surveys can cover the red-shift with the range $0 < z < 5$, the non-linear effects on the matter power spectrum are essential for the theoretical prediction of WL signal. In this study, we conducted a series of DM-only N-body simulations to accurately account for the non-linear effects on the matter power spectrum. The matter power spectrum can be modified by the elastic scattering of DM particle χ with proton p. The scattering cross-section, denoted as $\sigma_{\chi\mathrm{p}} \equiv \sigma_n v_{\mathrm{rel.}}^n$, is parameterized by a power-law index n and the relative velocity between DM and protons $v_{\mathrm{rel.}}$.

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A direct probe of Λ potential in nuclear medium

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Using the Liège intranuclear-cascade model together with the ablation model ABLA, an investigation is conducted into the effects of Λ potential in Λ-nucleus and Λ-hypernucleus-nucleus collisions across various beam energies. The findings show that the angle and transverse-momentum distributions of scattered Λ hyperon, the scattering cross section of the Λ hyperon in Λ-nucleus collisions as well as the rapidity distribution of Λ hyperon in Λ-hypernucleus-nucleus collisions are significantly influenced by the strength of the Λ potential in these scattering reactions across various beam energies. These demonstrations, unhindered by the uncertainties of Λ and hypernuclei productions in nuclear medium, allow for a direct investigation of the Λ potential, especially its momentum dependence. The criticality of probing the Λ potential is closely associated with the resolution of the "hyperon puzzle" in neutron stars.

Neutron stars emerge from the ashes of supernova explosions and were initially believed to predominantly consist of neutrons. Nonetheless, a sequence of theoretical studies has suggested that neutron stars might also harbor strange matter [1]. The concept of strangeness in neutron stars could profoundly impact our comprehension of these celestial bodies [2]. This aspect might influence their internal composition and cooling mechanisms, as highlighted in various studies [3–7]. Additionally, the presence of strangeness could alter the dynamics of neutron star mergers [8], potentially leading to distinct gravitational wave signatures [9]. The softening of the equation of state for dense matter, attributed to strangeness, could play a pivotal role in the shock-wave/neutrino-delayed-shock process, thereby affecting the explosive birth of core-collapse supernovae [10–13]. The presence of strangeness within neutron star matter has thus ignited the curiosity of the physics community [14–21], promising to shed light on the strong nuclear force and the characteristics of matter in ultra-extreme conditions, as further explored in references [19, 21–24]. Consequently, the study of hyperon-nucleon interactions and the significance of strangeness in neutron stars arises as a vital domain for astrophysicists, together with particle and nuclear physicists.

The resolution of the "hyperon puzzle", focusing on the inclusion of strangeness within the nuclear medium to ascertain the strong nuclear force, remains a fundamental query [22]. A variety of theoretical approaches have been adopted, such as utilizing nuclear many-body theories for calculating the properties of strange particles in dense environments [18, 24], applying effective field theories to elucidate the interactions between strange particles and nucleons [25], using perturbative quantum chromodynamics for the study of strange quark matter [26, 27]. Astrophysical observations of neutron stars also serve as a means to deduce the characteristics of strange particles within [28, 29].

Despite these methodologies, interactions between strangeness and non-strangeness in nuclear matter confront considerable theoretical ambiguities and are seldom directly examined through nuclear experiments in terrestrial labs. In Ref. [30], it is argued that combining studies of transport models with nuclear experimental data from facilities around the world could be a better way to address the "hyperon puzzle". Therefore, nuclear reactions may offer a more effective method for studying hyperon-nucleon interactions within nuclear medium: Hyperon-nucleus scattering experiments deal with hyperon-nucleon interactions in medium around saturation density, whereas hypernucleus-nucleus collisions examine these interactions at higher densities. By adjusting the beam energy, one can also explore the momentum dependence of hyperon-nucleon interactions in nuclear medium. In this study, the Liège intranuclear-cascade (INCL) model, combined with the ABLA deexcitation code, is employed to investigate the effects of the Λ potential around and above normal nuclear density. It's demonstrated that experiments involving Λ-nucleus and hypernucleus-nucleus collisions could directly unveil the Λ-nucleon interactions in nuclear medium.

The Liège intranuclear-cascade code, also known as the INCL model [31–33], is used to describe the collision between a projectile (such as nucleons, pions, hyperons and light ions) and a target nucleus. The INCL model incorporates classical physics principles, but also includes some quantum-mechanical features (such as Fermi motion, realistic space densities and Pauli blocking) to account for the initial conditions and dynamics of the collision. The INCL model treats an energy and isospin-dependent nucleon potential and an isospin-dependent constant hyperon potential with Woods-Saxon density distributions [32, 34, 35]. The model treats nuclear collisions as successive relativistic binary hadron-hadron collisions, where the positions and momenta of the hadrons are tracked over time. The extended INCL model includes the production of pion mesons and strange particles [36, 37]. The latest version of the model, INCL++6.32, includes the formation of hyperremnants [38, 39]. Based on different kinds of conservation laws (such as for baryon number, charge, energy, momentum, and angular momentum), the model predicts the formation of hot hyperremnants and characterizes them in terms of atomic and mass numbers, strangeness number,

Relativistic fluctuations in stochastic fluid dynamics

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Abstract. The state-of-the-art theoretical formalism for a covariant description of non-Gaussian fluctuation dynamics in relativistic fluids is discussed.

1 Introduction

Fluctuating hydrodynamics is a powerful tool for exploring complex and critical phenomena in non-equilibrium systems that possess a small number of degrees of freedom. Such scenarios are realized in relativistic heavy-ion collisions where a few thousand particles are produced, especially when the hypothetical QCD critical point is approached. Therefore, fully establishing the framework for relativistic fluctuating hydrodynamics is necessary for interpreting observables in experiments that are sensitive to fluctuations and criticality. Developing a covariant description of non-Gaussian fluctuation dynamics in stochastic fluids is a crucial step toward achieving this ambitious goal.

In this proceeding, we will briefly formulate the essential theoretical development of deterministic fluctuating hydrodynamics from a general perspective. More specifically, we will begin by reviewing the results of Ref. [1] in Sec. 2.1 and 2.2, where we presented the covariant formalism for the non-equilibrium evolution of non-Gaussian fluctuations in relativistic fluids. It on one hand follows the approach used in earlier work [2] and [3], where the covariant dynamical description was developed but only for Gaussian fluctuations, and on the other hand extends the subsequent work [4], where a generic formalism for non-Gaussian fluctuation dynamics was established, yet it has not been implemented covariantly. In Sec. 2.3, we will illustrate how the number of independent n-point correlation functions can be significantly reduced, upon the use of certain approximation which facilitates easier numerical implementation. We shall keep the formulation as general as possible, allowing it to be applied to arbitrary n and regimes not relying on the separation of relaxation time scales.

2 Theoretical framework

2.1 Fluctuation evolution equations

We start from the *covariant* Langevin equation for a set of stochastic fields ψ_i (such as conserved quantities including charge density and energy-momentum density) where the

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Article

Constraints on the mass of a bosonic dark matter candidate within the DD2Y-T model

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Abstract: Dark matter remains a topic of ongoing controversy. It has gained attention in the theoretical description of compact objects such as neutron stars with cores of very dense matter. Various candidates have been proposed for dark matter in the scientific literature. Among them, the sexaquark has been identified as a potential bosonic particle capable of being formed in neutron star matter based on its mass characteristics. In this study, we investigate the viability of the sexaquark as a candidate for dark matter, particularly under certain density conditions. Our goal is to address the challenges associated with the formation of a bosonic particle in a highly dense medium without compromising the stability of the neutron star. To achieve this, we introduce a straightforward linear mass shift for the sexaquark within the hadronic equation of state, utilizing a relativistic density functional approach. In our investigation, it is observed that the inclusion of Sexaquark as a candidate for dark matter within the hadronic matter equation of state, although featuring a repulsive interaction with baryonic matter, softens the equation of state. We suppose that the strength of the interaction of dark matter with baryonic matter increases linearly with the baryon density. We observe that raising the effective mass of the Sexaquark, as a result of increasing its vacuum mass, causes an increased stiffening of the equation of state as compared to the case of a constant mass. We determine the lower and upper mass boundaries for this bosonic dark matter based on observational constraints for neutron stars within the DD2Y-T model when a phase transition to quark matter phase is employed.

Keywords: Dark matter, Neutron star, Equation of State, Relativistic Mean-Field, Phase transition, Sexaquark

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1. Introduction

The accepted cosmological models that are presented and founded in General Relativity (GR), suggest that almost 27% of the matter-energy composition of the universe exists in the form of enigmatic Dark Matter (DM) [1].

Multi-messenger astrophysics is actively engaged in the search for and examination of new ideas concerning dark-matter particles. These candidates are believed to be non-relativistic particles that exist beyond the Standard Model of particle physics. They interact weakly with ordinary baryonic matter solely through gravitational forces [2]. In this context, the most widely accepted candidates for DM are weakly interacting massive

The Collective Coordinate Fix

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Abstract

Collective coordinates are frequently employed in path integrals to manage divergences caused by fluctuations around saddle points that align with classical symmetries. These coordinates parameterize a manifold of zero modes and more broadly provide judicious coordinates on the space of fields. However, changing from local coordinates around a saddle point to more global collective coordinates is remarkably subtle. The main complication is that the mapping from local coordinates to collective coordinates is generically multi-valued. Consequently one is forced to either restrict the domain of path integral in a delicate way, or otherwise correct for the multi-valuedness by dividing the path integral by certain intersection numbers. We provide a careful treatment of how to fix collective coordinates while accounting for these intersection numbers, and then demonstrate the importance of the fix for free theories. We also provide a detailed study of the fix for interacting theories and show that the contributions of higher intersections to the path integral can be non-perturbatively suppressed. Using a variety of examples ranging from single-particle quantum mechanics to quantum field theory, we explain and resolve various pitfalls in the implementation of collective coordinates.

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Analytic solutions for the linearized first-order magnetohydrodynamics and implications for causality and stability

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Abstract: We solve the first-order relativistic magnetohydrodynamics (MHD) within the linear-mode analysis performed near an equilibrium configuration in the fluid rest frame. We find two complete sets of analytic solutions for the four and two coupled modes with seven dissipative transport coefficients. The former set has been missing in the literature for a long time. Our method provides a simple and general algorithm for the solution search on an order-by-order basis in the derivative expansion, and can be applied to general sets of hydrodynamic equations. We also find that the small-momentum expansions of the solutions break down when the momentum direction is nearly perpendicular to an equilibrium magnetic field due to the presence of another small quantity, that is, a trigonometric function representing the anisotropy. We elaborate on the angle dependence of the solutions and provide alternative series representations that work near the right angle. Finally, we discuss the issues of causality and stability based on our analytic solutions and recent developments in the literature.

Investigation of full-charm and full-bottom pentaquark states

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The continuous advancement of experimental techniques and investigations has led to observations of various exotic states in particle physics. Each addition to this family of states not only raises expectations for future discoveries but also focuses attention on such potential new states. Building upon this motivation and inspired by recent observations of various traditional and exotic particles containing an increased number of heavy quarks, our study provides a spectroscopic search for potential pentaquark states with spin-parity $\frac{3}{2}^-$ and composed entirely of charm or bottom quarks. We predict the masses for full-charm and full-bottom pentaquark states as $m = 7628 \pm 112$ MeV and $m = 21982 \pm 144$ MeV, respectively. We also compute the current couplings of these states to vacuum, which are main inputs in investigations of their various possible decays.

I. INTRODUCTION

Since the proposal of the quark model, hadrons with non-conventional structures, which do not fit the conventional baryons composed of three quarks (antiquarks) and mesons composed of a quark and an antiquark, have been subjects of interests. The theory of strong interaction does not rule out the existence of such states, and this has attracted interest in these states. They were investigated extensively in both theory and experiments. Finally, the first evidence came out with the observation of $X(3872)$ state in 2003 [1]. And following this observation, many other such exotic state candidates were observed [2–10] and listed in Particle Data Group (PDG) [11]. These observations were also followed by many theoretical investigations trying to explain their internal structures, which still have ambiguity and need to be clearly identified with more scrutiny. It is evident that we will come across with other such possible exotic states in the future. This expectation necessitates their examinations in detail via different approaches to provide an understanding of their substructure and properties and provide feedback for future investigations. Besides, these states help to deepen our understanding of the dynamics of the strong interaction.

The pentaquark states are among these non-conventional states with their first observation reported in 2015 by the LHCb collaboration [3]. The investigation of the $\Lambda_b^0 \to J/\psi p K^-$ process resulted in two pentaquark states in the $J/\psi p$ invariant mass spectrum with the following resonance parameters [3]: $m_{P_c(4380)^+} = 4380 \pm 8 \pm 29$ MeV, $\Gamma_{P_c(4380)^+} = 205 \pm 18 \pm 86$ MeV and $m_{P_c(4450)^+} = 4449.8 \pm 1.7 \pm 2.5$ MeV, $\Gamma_{P_c(4450)^+} = 39 \pm 5 \pm 19$ MeV. This observation was supported by a full amplitude analysis for $\Lambda_b^0 \to J/\psi p \pi^-$ decays [4] in 2016. In 2019, using updated data, a new pentaquark state, $P_c(4312)^+$, was reported with $m_{P_c(4312)^+} = 4311.9 \pm 0.7^{+6.8}_{-0.6}$ MeV and $\Gamma_{P_c(4312)^+} = 9.8 \pm 2.7^{+3.7}_{-4.5}$ MeV by the LHCb collaboration and analyses revealed two narrow overlapping peaks for the previously observed peak of the $P_c(4450)^-$ state with masses and widths: $m_{P_c(4440)^+} = 4440.3 \pm 1.3^{+4.1}_{-4.7}$ MeV, $\Gamma_{P_c(4440)^+} = 20.6 \pm 4.9^{+8.7}_{-10.1}$ MeV and $m_{P_c(4457)^+} = 4457.3 \pm 0.6^{+4.1}_{-1.7}$ MeV, $\Gamma_{P_c(4457)^+} = 6.4 \pm 2.0^{+5.7}_{-1.9}$ MeV [5]. In the recent investigations, new states with the strange quark were also added to this family. The LHCb collaboration reported the $P_{cs}(4459)^0$ state through the investigation of $J\psi\Lambda$ invariant mass distribution in $\Xi_b^- \to J/\psi K^- \Lambda$ decays [9]. The mass and width for the $P_{cs}(4459)^0$ were given as $m = 4458.8 \pm 2.9^{+4.7}_{-1.1}$ MeV, and $\Gamma = 17.3 \pm 6.5^{+8.0}_{-5.7}$ MeV [9]. $P_{cs}(4338)$ state was reported with the mass $4338.2 \pm 0.7 \pm 0.4$ MeV and the width $7.0 \pm 1.2 \pm 1.3$ MeV from the amplitude analyses of $B^- \to J/\psi \Lambda \bar{p}$ [10].

Following the observations of the above pentaquark states, theoretical researches chasing the purpose of identifying their various properties have focused on these states. The sub-structures and quantum numbers of these observed

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Neutrino zeromodes on electroweak strings in light of topological insulators

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Abstract: We examine neutrino zeromode solutions on the electroweak Z-string and their effect on the stability of the string in the standard model and its extensions. We propose using topological invariants constructed from the momentum (and real) space topology of Green's functions, often used for investigating edge modes in condensed matter physics. We analyze the standard model and then examine type-I and type-II extensions of the neutrino sector as well as their hybrid. Based on this analysis, we also comment on proposals in the literature to stabilize the Z-string.

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Hard-scattering approach to strongly hindered electric dipole transitions between heavy quarkonia

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Abstract

The conventional wisdom in dealing with electromagnetic transition between heavy quarkonia is the multipole expansion, when the emitted photon has a typical energy of order quarkonium binding energy. Nevertheless, in the case when the energy carried by the photon is of order typical heavy quark momentum, the multipole expansion doctrine is expected to break down. In this work, we apply the "hard-scattering" approach originally developed to tackle the strongly hindered magnetic dipole ($M1$) transition [Y. Jia *et al.*, Phys. Rev. D. 82, 014008 (2010)] to the strongly hindered electric dipole ($E1$) transition between heavy quarkonia. We derive the factorization formula for the strongly hindered $E1$ transition rates at the lowest order in velocity and α_s in the context of the non-relativistic QCD (NRQCD), and conduct a detailed numerical comparison with the standard predictions for various bottomonia and charmonia $E1$ transition processes.

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New Physics with PeV Astrophysical Neutrino Beams

By

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Abstract

Astrophysical neutrinos allow us to access energies and baselines that cannot be reached by human-made accelerators, offering unique probes of new physics phenomena. This thesis aims to address the challenges currently facing searches for Beyond Standard Model (BSM) physics in the high-energy universe using astrophysical neutrinos, particularly in the contexts of flavor measurements and connections with dark matter.

The search for new physics with astrophysical neutrinos requires as a prerequisite understanding standard neutrino sources, which remain ambiguous. We begin by performing a multi-wavelength search for astrophysical neutrino sources using nine years of IceCube data. We find hints of neutrino emission from radio-bright Active Galactic Nuclei (AGN), further supporting recent claims that neutrino emission occurs near the core of AGNs.

Next we turn our attention to BSM searches. Accurate flavor measurements of the astrophysical flux provide a smoking gun signature to BSM physics. This requires a precise measurement of the tau neutrino fraction. However, tau identification proved a major hurdle in the current generation of observatories. We confront the problem of astrophysical neutrino flavor measurements by first introducing `TauRunner`, a simulation tool that accurately models the propagation of tau neutrinos including previously neglected effects such as tau lepton energy losses and depolarization in matter. We show that better modeling of tau neutrino propagation improves IceCube transient point-source sensitivities by more than an order of magnitude at EeV energies, and diffuse flux sensitivities by a factor of two. Second, we use this software to model IceCube counterparts to anomalous events reported by the ANITA experiment. After performing an analysis using IceCube data, we show that all Standard Model explanations are ruled out. Looking ahead to the future of flavor measurements, we also present a study that predicts the production of tau neutrinos via the propagation of electron and muon neutrinos in Earth, finding an irreducible but quantifiable background to next-generation tau neutrino observatories.

Finally, we attempt to address the field's shared ignorance of the origin of neutrino and dark matter masses by exploring potential connections between the two. Specifically, we present an analysis of dark matter annihilation and decay to neutrinos. We obtain limits from MeV to ZeV masses using more than a dozen neutrino experiments. Notably, using recent data from the SuperKamiokande experiment, we place the first-ever limit on dark matter annihilation that reaches

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Revisiting $O(N)$ σ model at unphysical pion masses and high temperatures

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Roy-equation analyses on lattice data of $\pi\pi$ scattering phase shifts at $m_\pi = 391$MeV reveals that the lowest f_0 meson becomes a bound state under this condition. In addition, there is a pair of complex poles below threshold generated by crossing symmetry [1]. We use the N/D method to partially recover crossing symmetry of the $O(N)$ σ model amplitude at leading order of $1/N$ expansion, and qualitatively reproduce the pole structure and pole trajectories with varying pion masses as revealed by Roy-equation analyses. The σ pole trajectory with varying temperature is also discussed and found to be similar to its properties when varying m_π. As the temperature increases, the complex σ poles firstly move from the second Riemann sheet to the real axis becoming two virtual state poles, and then one virtual state pole moves to the first sheet turning into a bound state pole and finally tends to the pion pole position at high temperature which is as expected from the chiral symmetry restoration. Our results provide further evidences that the lowest f_0 state extracted from experiments and lattice data plays the role of σ meson in the spontaneous breaking of chiral symmetry. Finally, we also briefly discuss the problems of the effective potential in the situation when m_π and temperature get large.

I. INTRODUCTION

Chiral symmetry breaking plays an important role in the QCD low energy dynamics. It is already well-known that due to the smallness of the u and d quark masses, QCD possesses an approximate $SU(2)_L \times SU(2)_R$ chiral symmetry, and it is also well accepted that this symmetry is broken by the nonzero $\langle 0|\bar{q}q|0\rangle$ and three pesudo-Goldstone bosons are generated which are identified as the π mesons observed in the low energy hadron scatterings. Historically, the famous linear sigma model firstly proposed by Gell-Mann and Lévy in 1960 [2] could provide an effective field theory description of this symmetry. In this model, another scalar field σ is combined with the three pions to form a linear realization of an $O(4)$ symmetry and acquires a vacuum expectation value to break the $O(4)$ to $O(3)$, where the $O(4) \simeq SU(2)_L \times SU(2)_R$ can be identified as the previous chiral symmetry and the remaining $O(3)$ corresponds to the preserved $SU(2)_V$. For a long time, the existence of the σ particle was in controversy. The mild rise of the $\pi\pi$ phase shift can hardly be recognized as generated from a typical resonance. A broad resonance was proposed to describe the $\pi\pi$ scattering phase shift in 1960s, see for example [3–5]. However, such a broad resonance appeared and disappeared from the PDG table several times from the 1960s until 2000s. Another description using a nonlinear realization of the chiral symmetry [6, 7] in which the scalar-isoscalar particle is totally abandoned from the Lagrangian is the nowadays very popular chiral perturbation theory (χPT) [8, 9], which is regarded as the low energy effective theory of QCD. Within this formalism, the low energy properties of the pion-pion scattering, such as the scattering length, effective range, and phase shifts near the threshold can be reproduced. The low energy coupling constants can be saturated by integrating out vector resonances [10, 11] (see however [12, 13]). Thus, there seems to be no need to have a scalar-isoscalar particle in describing the low energy pion-pion scatterings. However, with energy going up, χPT blows up quickly. Fortunately, unitarity and dispersive techniques come to its rescue. After unitarization, the $IJ = 00$ channel $\pi\pi$ scattering amplitude dynamically generates a resonance state represented as a pair of conjugate poles on the second Riemann sheet, see for example [14, 15]. However, this kind of unitarized method always generates more poles than physically expected [16], especially spurious poles on the physical sheet, which cast doubts on the reliability of the results, not to mention the violation of crossing symmetry (for a recent review, see Ref. [17]). On the other hand, a novel model-independent analysis representing the partial wave S-matrix as a product of pole and the left-hand cut integral terms, showed that the left-hand cut estimated from χPT always produces a negative contribution to the phase shift while the data show a positive trend near the threshold, which demonstrates the necessity of a subthreshold resonance pole on the second sheet of the amplitude [18]. This method was further developed into the

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Minimal SU(5) theory on the edge: the importance of being effective

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It is well known that the minimal renormalizable $SU(5)$ grand unified theory is ruled out: it predicts same masses of down quarks and charged leptons, the gauge couplings do not unify and neutrinos are massless. We show here that all this can be cured simultaneously by the addition of higher-dimensional effective operators. However, the theory lives on the edge since the unification scale turns out as low as roughly 10^{14} GeV, threatening proton longevity. If the lower bound on the proton lifetime was to be increased by an order of magnitude, the usual desert in energies between the weak and unification scales would be populated. We also revisit two minimal extensions of this theory that offer a dynamical seesaw origin of neutrino mass, and discuss the resulting consequences.

I. INTRODUCTION

By unifying electro-weak and strong interactions in a single compact gauge group, grand unified theories (GUTs) explain the mystery of charge conjugation in nature and in turn predict the existence of magnetic monopoles [1, 2]. Moreover, they imply proton decay and provide a rough estimate of its lifetime, tantalizingly close to the present experimental limits [3].

While there are many models on the market, the original $SU(5)$ theory of Georgi and Glashow [4] stands out due to its simplicity and predictivity. Actually, in its simplest renormalizable form, it is predictive enough to be ruled out by experiment due to two fundamental failures: it predicts equal masses for charged leptons and down quarks, and gauge couplings do not unify - α_1 meets α_2 too early, contrary to what seemed originally [5]. Furthermore, neutrinos end up being massless, but that can be cured by adding fermion singlets - without altering the gauge structure of the theory - which through the seesaw mechanism [6–10], naturally provide small neutrino masses.

There are two distinctive ways of potentially salvaging the theory. One is to add more fields, and take a road of model building, a field interesting in itself - something, however, we will not pursue here. Alternatively, one can employ higher-dimensional effective operators to correct the bad fermion mass relations [11] and provide non-vanishing neutrino masses [12], and even ensure gauge coupling unification [13].

We follow here the latter road and reanalyze the minimal $SU(5)$ theory, augmented by dimension $d = 5$ operators. A rather low unification scale and seemingly too rapid proton decay, prompted a belief that the theory was ruled out, repeated often over the years. The point, however, is that proton could be stable in the limit of the tiny third generation CKM angle going to zero [14], in which case, proton lifetime would be enhanced by some five orders of magnitude. This has been discussed at length [15–19], but still, no serious attempt was made to verify the validity of the theory. After all, it was failing on three fronts as we mentioned above, and it all indicated that it could not survive experimental challenges. And so, the theory kept being sentenced to death by experts, including the present authors (especially one of them [20]). By today it became a gospel - the most recent review of proton decay [21] even cites an extension of this theory as the minimal one.

We show, however, that there exists a region of parameter space where this theory is still phenomenologically viable. It lives on the edge though - an experimental improvement on proton lifetime limit by a factor 10 (20) would point towards the existence of a new light scalar state, the color octet or the weak triplet, below 100 TeV (10 TeV) energies. In other words, the infamous desert at energies between the weak and the GUT scales would not exist in this case, and further improvements on proton lifetime limits could finally rule out the remaining region of the parameter space. Until that happens, we believe that desires to bury what is arguably the minimal grand unified theory, should be put to rest.

The rest of this work, devoted to demonstrating our claim, is organized as follows. In the next Section, the central features of the minimal $SU(5)$ theory are summarized. In Sec. III, its gauge-coupling running is analyzed, with particular focus on the impact of particle thresholds, as well as the effect of $d = 5$ operators on unification conditions. Sec. IV discusses the flavour of proton decay, and its constraints on the unification scale. In Sec. V, we revisit the predictions of two minimal models that generate neutrino mass through renormalisable interactions. Our findings are summarized in Sec. VI.

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FKS subtraction for quarkonium production at NLO

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Abstract: We extend the local infrared-divergence subtraction formalism, originally proposed by Frixione, Kunszt and Signer (FKS), to calculate short-distance (differential) cross section for any inclusive process involving a quarkonium particle in non-relativistic QCD (NRQCD) factorisation at next-to-leading order (NLO) accuracy in the strong coupling constant α_s. The new formulas are generally applicable to the production of an S- or P-wave quarkonium state in association with any number of elementary particles. The main new ingredients derived in this paper are the local and integrated soft counterterms for the colour-singlet and colour-octet P-wave bound states. It, therefore, paves the way to the automation of the NLO calculations for heavy quarkonium inclusive and associated production processes.

Keywords: NLO Computations, IR divergences, Quarkonium, QCD, NRQCD

Deciphering the Belle II data on $B \to K\nu\bar{\nu}$ decay in the (dark) SMEFT with minimal flavour violation

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Abstract: Recently, the Belle II collaboration announced the first measurement of the branching ratio $\mathcal{B}(B^+ \to K^+\nu\bar{\nu})$, which is found to be about 2.7σ higher than the Standard Model (SM) prediction. We decipher the data with two new physics scenarios: the underlying quark-level $b \to s\nu\bar{\nu}$ transition is, besides the SM contribution, further affected by heavy new mediators that are much heavier than the electroweak scale, or amended by an additional decay channel with undetected light final states like dark matter or axion-like particles. These two scenarios can be most conveniently analyzed in the SM effective field theory (SMEFT) and the dark SMEFT (DSMEFT) framework, respectively. We consider the flavour structures of the resulting effective operators to be either generic or satisfy the minimal flavour violation (MFV) hypothesis, both for the quark and lepton sectors. In the first scenario, once the MFV assumption is made, only one SM-like low-energy effective operator induced by the SMEFT dimension-six operators can account for the Belle II excess, the parameter space of which is, however, excluded by the Belle upper bound of the branching ratio $\mathcal{B}(B^0 \to K^{*0}\nu\bar{\nu})$. In the second scenario, it is found that the Belle II excess can be accommodated by 22 of the DSMEFT operators involving one or two scalar, fermionic, or vector dark matters as well as axion-like particles. These operators also receive dominant constraints from the $B^0 \to K^{*0} + \text{inv}$ and $B_s \to \text{inv}$ decays. Once the MFV hypothesis is assumed, the number of viable operators is reduced to 14, and the $B^+ \to \pi^+ + \text{inv}$ and $K^+ \to \pi^+ + \text{inv}$ decays start to put further constraints on them. Within the parameter space allowed by all the current experimental data, the q^2 distributions of the $B \to K^{(*)} + \text{inv}$ decays are then studied for each viable operator. We find that the resulting prediction of the operator $\mathcal{Q}_{q\chi} = \left(\bar{q}_p\gamma_\mu q_r\right)\left(\bar{\chi}\gamma^\mu\chi\right)$ with a fermionic dark matter mass $m_\chi \approx 700\,\text{MeV}$ can closely match the Belle II event distribution in the bins $2 \leq q^2 \leq 7\,\text{GeV}^2$. In addition, the future prospects at Belle II, CEPC and FCC-ee are also discussed for some of these FCNC processes.

Magnetic catalysis and diamagnetism from pion fluctuations

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In the framework of Nambu–Jona-Lasinio model beyond mean field approximation, the effects of pion fluctuations on (inverse) magnetic catalysis and magnetic susceptibility are studied. The negative magnetic susceptibility at low temperature is observed when contributions from both neutral and charged pions are taken into account. In weak field approximation, it is observed that at finite temperature, the magnetic inhibition effect in the chiral limit, resulting from the difference between the transverse and longitudinal velocities of neutral pions, converts to weak magnetic catalysis when considering a non-zero current quark mass. Moreover, the magnetic catalysis is amplified by the charged pions.

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I. INTRODUCTION

The investigation of the response of quark matter to a uniform magnetic field background has been a hot topic for the last decade, see reviews [1–5]. In the experimental aspect, a strong but transient magnetic field can be generated in the initial stage of heavy ion collisions (HIC), which was believed to be the strongest magnetic field ever created, with the strength of $eB \sim 10^{18-20}$ Gauß and life time of 10^{-22} second [6–10]. In the theoretical aspect, the interplay between a magnetic field and quantum chromodynamics (QCD) can lead to various novel behaviors and can be used as a probe to investigate the inner structure of quark matter.

The surge of the interest in studying the influence of magnetic field to a equilibrium system starts from two abnormal results from a lattice QCD group's ab-initio calculation, (i) although the vacuum quark mass is enhanced by the magnetic field, the chiral critical temperature decrease with the increasing of it, which is called inverse magnetic catalysis (IMC), (ii) the magnetic susceptibility is negative at low temperature while positive at high temperature [11–16]. These results disagree with most of the effective model predictions at that time, for instance, the standard Nambu-Jona-Lasinio (NJL) model and linear-σ model with quark (Quark-Meson model) under mean-field approximation[17, 18].

Numerous studies have been conducted to elucidate the IMC and diamagnetic effects. These investigations have explored various mechanisms, including magnetic inhibition resulting from fluctuations of neutral pions [19], chirality imbalance stemming from sphaleron transitions or instanton-anti-instanton pairings [20, 21], and the influence of the running coupling constant in the presence of a magnetic field [22]. Some groups tried to include the anomalous magnetic moment effect [23–30] or the effect of tensor channel [26] in the NJL model to reproduce the IMC or diamagnetism. By considering the running coupling with eB-dependence fitted by lattice QCD data, the IMC result can be successfully reproduced in [31–38]. Hadron resonance gas (HRG) model, where the hadrons are assumed as point-like particles with no interaction in between, can also reproduce diamagnetic result at low temperature region [39, 40]. Functional continuum field approaches, such as the functional renormalization group (FRG), Dyson-Schwinger equations (DSE), and holographic QCD models also have made great efforts on both the effective models [39, 41–45] and QCD theory [46–48]. In general, the understanding of the IMC and diamagnetic effects remains an open question.

Most of the work in the NJL model was done based on the mean-field approximation which only considers the lowest-order in $1/N_c$ expansion [49]. In next-to-leading order of this expansion, the feedback effect from mesons is taken into consideration [50, 51]. Generally, mean field approximation for quark together with random phase approximation for meson works well to describe the thermodynamic properties of QCD matter in absence of magnetic field. For the puzzle of IMC and diamagnetism, the feedback from mesons can be part of the solution, given that they are influenced by magnetic field in both direct (for charged mesons) and indirect (for neutral mesons) manners [38, 52–58]. In references [19, 59, 60], the feedback effect from π_0 with a physical propagating velocity is included in the chiral limit, giving an IMC result. Besides, in the (Polyakov-loop extended) quark-meson model, the meson fluctuations, especially the light pion contributions, lead to the diamagnetism [39, 42]. In our calculation, we investigated beyond mean field by including the effect from both π_0 and $\pi^{\pm}$ with and without finite propagating velocities, and consider a physical situation where chiral symmetry is explicitly broken, to see their role in (inverse) magnetic catalysis and magnetic susceptibility.

This paper is arranged as follows: In Sec. II we introduce the calculating procedure in beyond mean-field NJL model in the manner of weak-field expansion. In Sec. III, we give the numerical results for eB-dependence of critical temperature T_c and magnetic susceptibility followed

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Study of Long Range Force in P2SO and T2HKK

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Abstract

In this paper we have studied the sensitivity of the future long-baseline neutrino experiments P2SO and T2HKK to the long-range force (LRF). In the context of these two experiments, our aim is to study: (i) the capability to put bounds on the LRF parameters, (ii) effect of LRF in the measurement of standard oscillation parameters and (iii) capability to constrain the mass of the new gauge boson and the value of new coupling constant, that gives rise to LRF due to matter density in Sun. In our study, we find that among the different neutrino experiments, the best bound on the LRF parameters including mass of the new gauge boson and the value of new coupling constant will come from the P2SO experiment. Our study also shows that LRF has non-trivial effect on the determination of the standard neutrino oscillation parameters except the precision of Δm^2_{31}. For this parameter, the precision remains unaltered in the presence of LRF for both these experiments.

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Photon-Odderon interference in exclusive χ_c charmonium production at the Electron-Ion Collider

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Exclusive $C = +1$ scalar, axial-vector, and tensor quarkonium production in high-energy electron-proton scattering requires a C-odd t-channel exchange of a photon or a three gluon ladder. We derive the expressions for the corresponding amplitudes. The relative phase of the photon vs. three gluon exchange amplitudes is determined by the sign of the light-front matrix element of the eikonal color current operator $d^{abc} J^{+a} J^{+b} J^{+c}$ at moderate x, and is not affected by small-x QCD evolution. Model calculations predict constructive interference, which is particularly strong for momentum transfer $|t| \sim 1$ GeV^2 where the cross section for χ_{cJ} production exceeds that for pure photon exchange by up to a factor of 4. We find that exclusive χ_{cJ} electroproduction at the Electron-Ion Collider should occur with well measurable rates and measurements of these processes should allow to find an evidence of the perturbative Odderon exchange. We also compute the total electroproduction cross section as a function of energy and provide first estimates of the number of χ_{cJ} events per month at the Electron-Ion Collider design luminosity.

CONTENTS

Charged Lepton Flavor Violation in the B-L symmetric SSM

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Abstract

Charged lepton flavor violation (CLFV) represents a clear new physics (NP) signal beyond the standard model (SM). In this work, we investigate CLFV processes $l_j^- \to l_i^-\gamma$ utilizing mass insertion approximation(MIA) in the minimal supersymmetric extension of the SM with local B-L gauge symmetry (B-LSSM). The MIA method can provide a set of simple analytic formulae for the form factors and the associated effective vertices, so that the movement of the CLFV decays $l_j^- \to l_i^-\gamma$ with the sensitive parameters will be intuitively analyzed. Considering the SM-like Higgs boson mass and the muon anomalous dipole moment (MDM) within 4σ, 3σ and 2σ regions, we discuss the corresponding constraints on the relevant parameter space of the model.

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Keywords: Supersymmetric Model, Charged Lepton Flavor Violation, Muon Magnetic Dipole Moment

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Features of strangeness production in pp and heavy ion collisions

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Based on the existing experimental data for A-A collisions starting from the Alternating Gradient Synchrotron up to the CERN Large Hadron Collider energies, various systematics related to strange hadrons and anti-hadrons are presented. As in the case of pions, kaons and protons, the ratio between the average transverse momentum and the square root of the total particle multiplicity per unit rapidity and unit transverse overlap area $\langle p_T\rangle/\sqrt{\langle dN/dy\rangle/S_\perp}$ as a function of collision energy for a given centrality or as a function of centrality for a given collision energy supports the predictions of color glass condensate and percolation based approaches. The dependence on $\sqrt{\langle dN/dy\rangle/S_\perp}$ of the slope and offset, extracted from the $\langle p_T\rangle$ - particle mass correlation and the average transverse expansion velocity and kinetic freeze-out temperature parameters obtained from Boltzmann-Gibbs Blast Wave fits of the p_T spectra, for strange hadrons, is compared to that for pions, kaons and protons, previously studied.

The detailed study of the entropy density ($\langle dN/dy\rangle/S_\perp$) dependence of the ratio of strange hadron yields per unit rapidity to the total particle multiplicity per unit rapidity ($Y^S/\langle dN/dy\rangle$) at different collision energies and centralities reveals the necessity to study separately strange hadrons and anti-hadrons. The correlation between the ratio of the single- and multi- strange anti-hadron yield per unit rapidity to the total particle multiplicity per unit rapidity and the entropy density is presented as a function of the fireball size. A maximum is evidenced in the $Y^S/\langle dN/dy\rangle$ - $\langle dN/dy\rangle/S_\perp$ correlation for combined and separate species of strange hadrons, at different centralities, in the region where a transition from the baryon-dominated matter to the meson-dominated one takes place. Within the experimental error bars, the position of this maximum does not depend on the mass of the corresponding strange hadron. Comparison with pp experimental data reveals another similarity between pp and Pb-Pb collisions at the CERN Large Hadron Collider energies.

I. INTRODUCTION

The possibility to produce hot and dense matter in heavy ion collisions [1] such that, based on Quantum Chromo-Dynamics (QCD) asymptotic freedom properties, a transition from the hadronic phase to a high density "quark soup" [2, 3] or "quark-gluon plasma" [4] has motivated an unprecedented international effort in building accelerator facilities and complex experimental devices. The objects produced in such collisions have a size at the fermionic level, are highly inhomogeneous and undergo violent dynamics. Therefore, specific experimental probes have to be studied and theoretical approaches, combining different hypotheses for different stages of the formation and evolution of such systems produced in heavy ion collisions, are required for an unambiguous conclusion. The first estimates of the transition from a gas of free nucleons to hadronic matter and subsequently to deconfined matter as a function of density were done within the percolation approach [5, 6]. Phenomenological models predicted some discontinuities in the behaviour of different observables as a function of collision energy or centrality specific for a phase transition between two thermodynamic states in a closed volume [7–9]. Recently, based on the existing experimental results from the Alternating Gradient Synchrotron (AGS), Super Proton Synchrotron (SPS), BNL Relativistic Heavy Ion Collider (RHIC) and CERN Large Hadron Collider (LHC), it was evidenced such a trend in the dependence of the ratio of the energy density to the entropy density ($\langle dE_T/dy\rangle/\langle dN/dy\rangle$) as a function of entropy density at different collision centralities for A-A collisions [10]. The ratio of the energy density to the entropy density, at a given value of the transverse overlap area, increases with entropy. A tendency towards saturation at values of the entropy density beyond 6-8 fm^{-2}, corresponding to the largest collision energies at RHIC, and a steep rise at the LHC energies is evidenced for central collisions. Worth mentioning that for central collisions, a change in the collision energy dependence of the ratio $(1 - R_{AA}^{\pi^0})/\langle dN/dy\rangle$ [11] takes place in the same energy range as the one corresponding to the transition from an increase to the saturation in the entropy density dependence of the $\langle dE_T/dy\rangle/\langle dN_{ch}/dy\rangle$. Such trends are in qualitative agreement with theoretical model predictions [8, 9] and [12–14], respectively. 40 years ago, well before the experimental data became available, the enhancement of the strangeness production was advocated as sensitive probe for deconfinement [15]. A series of experiments, from SPS to LHC energies evidenced an enhancement of strange hadron production as a function of centrality relative to the one corresponding to the pp minimum bias collision at the same energy. The influence of the core-corona relative contribution on the centrality dependence of the strangeness production, average transverse momenta, elliptic flow or p_T spectra in heavy-ion collisions at SPS, RHIC and LHC energies was reported in many papers [16–28]. As far as con-

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Cosmic Inflation, Dark Energy and Gravitational Waves

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We briefly discuss cosmic inflation, which is the dominant paradigm for the generation of the large scale structure in the Universe and also for arranging for the initial conditions of the hot Big Bang. We then present quintessential inflation, which also accounts of the observed dark energy. We discuss how quintessential inflation can be successfully modelled in modified gravity in the Palatini formalism. Finally, we focus on the generation of primordial gravitational waves by inflation and how their spectrum can be enhanced when the early Universe goes through periods of stiff equation of state. This results in gravitational waves with a characteristic spectrum, which may well be observed in the near future, providing insights for the background theory.

PACS numbers: Suggested PACS
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1. COSMIC INFLATION

The history of the Universe requires special initial conditions, which are arranged by cosmic inflation [1, 2]. In a nutshell, cosmic inflation can be defined as a period of accelerated expansion in the Early Universe [3, 4]. Inflation produces a Universe which is large, uniform and spatially flat according to observations. Typically, inflation is realised via the inflationary paradigm, which states that the Universe inflates when dominated by the potential energy density of a scalar field, called the inflaton field.

The Klein-Gordon equation of motion of a homogeneous scalar field ϕ is

$$\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0\,, \qquad (1)$$

where H is the rate of the Universe expansion (Hubble parameter), the dot denotes derivative with respect to the cosmic time t and the prime denotes derivative with respect to the field: $' \equiv \partial/\partial\phi$. The above is of the same form as the equation of motion of a ball sliding down a potential under friction determined by H (see Fig. 1). Potential domination, therefore, suggests that the kinetic energy density is subdominant to the potential energy density V, and the field slowly rolls (slowly varies in field space) down a potential plateau, called the inflationary plateau. Inflation ends at a characteristic value $\phi_{\rm end}$ when the potential becomes steep and curved. After the end of inflation, the inflaton field oscillates around its vacuum expectation value (VEV). These coherent oscillations amount to inflaton particles, which decay into the primordial plasma, through a process called reheating.

Inflation however, should not make the Universe perfectly uniform, because in order for galaxies to form, initial perturbations in the density of the Universe are needed. Indeed, inflation makes the Universe largely uniform but also introduces minor deviations from uniformity which give rise to the Primordial Density Perturbations (PDPs), which in turn become the seeds for the formation of structures such as galaxies [4]. Inflation does this through the particle productions process which roughly operates as follows:

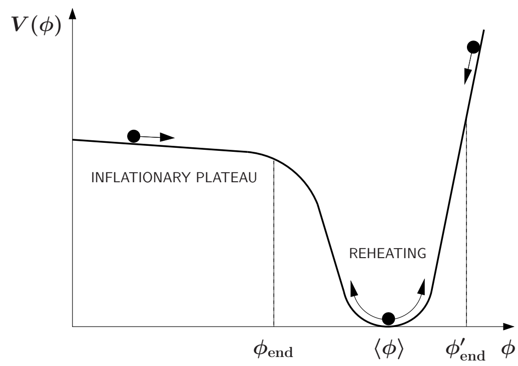

Figure 1. Sketch of the typical inflationary potential. Due to the form of the equation of motion (1), we can envisage the system as a ball rolling down a flat region of the potential, called the inflationary plateau. At some critical value of the inflaton field $\phi_{\rm end}$, the potential becomes steep and curved such that inflation is terminated. Afterwards, the field oscillates around its vacuum expectation value $\langle\phi\rangle$. The figure also depicts the possibility that the inflaton field slow-rolls down a steep potential under excessive friction (and inflation ends when this friction is not enough for inflation at $\phi'_{\rm end}$) but this possibility is not favoured by the observations.

Accelerated expansion of space is superluminal. This superluminal expansion during inflation amplifies the quantum fluctuations of the inflaton field, which become classical perturbations of the field through quantum decoherence. Consequently, inflation continues a little bit more in some locations than in others. Thus, at the end of inflation space expands in a different way in neighbouring locations, which introduces the PDPs (see Fig. 2).

The PDP reflects itself onto the Cosmic Microwave Background radiation (CMB) through the Sachs-

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Slicing Pomerons in ultraperipheral collisions using forward neutrons from nuclear breakup

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We argue that measurements of forward neutrons from nuclear breakup in inclusive high energy photon-nucleus (γA) scattering provide a novel complementary way to study small-x dynamics of QCD in heavy-ion ultraperipheral collisions (UPCs). Using the leading twist approximation to nuclear shadowing, we calculate the distribution over the number of evaporation neutrons produced in γPb collisions at the LHC. We demonstrate that it allows one to determine the distribution over the number of wounded nucleons (inelastic collisions), which constrains the mechanism of nuclear shadowing of nuclear parton distributions.

PACS numbers:
Keywords: Heavy-ion scattering, ultraperipheral collisions, nuclear shadowing

I. INTRODUCTION AND MOTIVATION

Understanding of the QCD dynamics of hard high energy interactions and the structure of nuclei and nucleons is one of the main directions of theoretical and experimental studies at the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC). Of particular interest is the limit of very small momentum fractions x, when the linear Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) approximation is expected to break down [1, 2] and a regime close to the black disk limit (BDL) [3] may set in. Its observation is one of the prime objectives of the planned Electron-Ion Collider (EIC) at Brookhaven National Laboratory [4, 5], which will ultimately reach $x \sim 10^{-3}$ for momentum transfers of a few GeV. At the same time, it was pointed out some time ago that ultraperipheral collisions (UPCs) of two ions at the LHC, where a photon emitted by one of the nuclei interacts with the other nucleus, allow one to probe down to $x \sim 10^{-5} - 10^{-4}$, depending on a particular reaction channel and the detector geometry [6, 7].

Electron-nucleus collisions at the EIC and UPCs of heavy ions at the LHC present two options for studying small-x dynamics, which are largely complementary. At the LHC practically all data are collected for one heavy nucleus and one cannot directly access the dependence of cross sections on the virtuality of the probe. At the same time, one can reach very small x, which is provided by a wide rapidity coverage of the LHC detectors and the large invariant photon-nucleus collision energies exceeding by a factor of 100 the design energies at the EIC.

Over the last decade the data taken in the LHC and RHIC kinematics discovered a significant nuclear suppression of coherent J/ψ photoproduction in Pb-Pb and Au-Au UPCs compared to the impulse approximation prediction [8–17]. When interpreted in the leading twist approximation (LTA) [18], it amounts to strong gluon nuclear shadowing [19, 20]:

$$R_A^g(x, Q^2) = \frac{g_A(x, Q^2)}{A g_N(x, Q^2)} < 1 \,, \tag{1}$$

where $g_A(x, Q^2)$ and $g_N(x, Q^2)$ are the nucleus and nucleon gluon densities, respectively. Typical numbers reported by the LHC experiments [8–16] correspond to

$$\begin{aligned} R_{\rm Pb}^g(x = 10^{-3}, Q_{\rm eff}^2 = 3\,{\rm GeV}^2) &\approx 0.6 \,, \\ R_{\rm Pb}^g(x = 10^{-4}, Q_{\rm eff}^2 = 3\,{\rm GeV}^2) &\approx 0.5 \,, \end{aligned} \tag{2}$$

with a similar suppression extending down to $x \sim 10^{-5}$. Here $Q_{\rm eff}$ is the effective resolution scale determined by the charm quark mass. These values of $R_{\rm Pb}^g$ agree very well with the LTA predictions for nuclear shadowing made more than 10 years ago [18]. Note that this interpretation of the J/ψ UPC data is complicated at the next-to-leading order (NLO) of the perturbative expansion in powers of $\log Q^2$ (perturbative QCD) due to large cancellations between the leading-order (LO) and NLO gluon terms, which leaves a numerically important quark contribution [21, 22]. A way to

Nuclear medium meson structures from the Schwinger proper-time Nambu–Jona-Lasinio model

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In this paper, we study the nuclear medium modifications of the meson electromagnetic form factors in the framework of the Nambu–Jona-Lasinio (NJL) model with the help of the Schwinger proper-time regularization scheme to tame loop divergence and simulate the effect of QCD confinement. In our current approach, the meson structure and nuclear medium are constructed in the same NJL model at the quark level. We examine the free space and in-medium charge radii for the kaon and pion, in addition to the spacelike elastic electromagnetic form factors of the kaon and pion as well as their quark-sector form factors, which reflect their internal structure. By comparing to the experimental data, we found that the free space elastic electromagnetic form factors for the mesons are consistent with the data, while the in-medium elastic electromagnetic form factors of the mesons are found to decrease as the nuclear matter density increases, leading to increase of meson charge radius, which is consistent with the prediction of other theory calculations. We also predict the axial nucleon coupling constant g_A in nuclear medium computed via the Goldberger-Treiman relation (GTR), which is crucial for the search for the neutrinoless double beta decay ($0\nu\beta\beta$).

I. INTRODUCTION

Kaons and pions play an important role in the description of the low-energy dynamics and properties of the strong interactions nonperturbative QCD [1] such as color QCD confinement and dynamical chiral symmetry breaking (DχSB), which are related to the so-called hadron mass generation or emergent hadron mass (EHM) [2]. In the nuclear medium, it is expected the partial restoration of the chiral symmetry breaking to occur at higher nuclear matter density. However, the question of how the restoration mechanism happens in the nuclear medium and how it will affect the structure of hadron remains unresolved and is still poorly understood. It is widely known that not only the weak properties of hadrons are modified in a nuclear medium, but also the structure of hadrons is expected to change, as observed for the first time by the Stanford Linear Accelerator Center (SLAC) experiment, which is then so-called as the European Muon Collaboration (EMC) effect [3, 4].

In the past many studies on kaon and pion properties in nuclear medium have been made within the various theoretical models, such as the hybrid light-front–quark-meson coupling (LF-QMC) model [5, 6], the QCD sum rules [7], the hybrid light-front constituent quark–quark-meson coupling (LFCQM-QMC) model [8], and the hybrid Nambu–Jona-Lasino–quark meson coupling (NJL-QMC) model [9, 10]. In the literature, most of those studies and attempts have made use of the hybrid model, meaning in their calculation they combined two different models in calculating the nuclear matter and the structure of hadron. For instance, the authors of Ref. [5] studied the pion structure using the LF-QMC model, where the LF model is used to calculate the pion structure in a relativistic manner, on one hand, and the QMC model is used to calculate the quark mass properties in the nuclear medium, on the other hand. It is worth mentioning that in the QMC model, the light quark is coupled to the strong scalar and vector meson mean fields to yield the medium quark masses. However, the dynamical spontaneous chiral symmetry breaking that dynamically generates the constituent quark mass is not clearly described in both LF and QMC models. The authors in Ref. [11] have tried to capture this quark condensate in the QMC model through the NJL model, where the dynamical symmetry breaking is well explained in the model. In the present study, we consistently calculate the meson elastic electromagnetic form factors and nuclear matter in the NJL model, where, in the NJL model, dynamical spontaneous chiral symmetry breaking and its partial restoration in the nuclear medium are captured in the chiral quark condensate as the order parameter quantity.

In this paper, we evaluate the kaon and pion properties and their medium modifications of the electromagnetic form factors using the NJL model with the help of the Schwinger proper-time regularization scheme. In the calculation, besides the meson structure, the nuclear medium is also computed using the NJL model. The NJL model is an uncomplicated model and very useful tool. The NJL model has been widely and successfully used to describe number of physics phenomena such as kaon and pion parton distribution functions [12], gluon distribution functions for the kaon and pion [13, 14], gluon EMC effects in nuclear matter [15, 16], color superconducting in neutron star [17–19], charge symmetry breaking effect in the pion and kaon structures [20], transverse momentum dependent (TMD) quark distribution function [21], transverse momentum dependent fragmenta-

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Light quarkonium hybrid mesons

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We investigate the light quarkonium hybrid mesons of various spin-parities in QCD. Considering different interpolating currents made of the valence light quarks and single gluon, we calculate the mass and current coupling of the strange and nonstrange members of light hybrid mesons by including into computations the nonperturbative quark and gluon condensates up to ten dimensions in order to increase the accuracy of the results. The obtained results may be useful for future experimental searches of these hypothetical states. They can also be used in the calculations of different parameters related to the decays/interactions of light hybrid mesons to/with other states.

I. INTRODUCTION

As successful theory of strong interaction, the quantum chromodynamics (QCD) together with the powerful quark model have predicted the existence of exotic hadrons beyond the standard mesons and baryons. The most known categories for exotic hadrons are tetraquarks, pentaquarks, hexaquarks, quark-gluon hybrids and glueballs. Starting from 2003, many tetraquark and pentaquark states have been discovered in the experiment. Concerning the hexaquarks, WASA-at-COSY collaboration has reported observation of a six-quark candidate $d^*(2380)$ with $J^P = 3^+$ [1], starting a wide research on the properties of hexaquarks and dibaryons as interesting objects: a hypothetical SU(3) flavor-singlet, highly symmetric, deeply bound neutral particle termed the scalar hexaquark $S = uuddss$ has been introduced as a potential candidate for dark matter [2]. Although some resonances have been introduced as the potential condidates for the hybrids and glueballs, there is no discovered particles with high confidence level in these categories yet. It is time to investigate the hybrid states and glueballs with a fresh breath, though they are searched for a long time. Hybrid states was predicted in 1976 [3]. There are some states with quantum numbers $J^{PC} = 0^{--}$, 0^{+-}, 1^{-+}, 2^{-+}, which cannot be explained by $q\bar{q}$ picture and are considered as potential hybrid meson candidates [4]. Among them are $\pi_1(1400)$ [5], $\pi_1(1600)$ [6], $\pi_1(2015)$ [7], and $\eta_1(1855)$ [8] with exotic quantum numbers $J^{PC} = 1^{-+}$ evidenced by some experiments. They are possible single-gluon hybrid candidates of a quark-antiquark pair together with a valence gluon. Designed to search for the hybrid mesons as its primary goal, the GlueX experiment at Jefferson Lab is expected to give crucial insights into the existence and structure of the exotic hybrid mesons.

Investigation of the light and heavy hybrid mesons is of great importance not only for determination of their nature and quark-gluon organization but for gaining useful information about the nonperturbative nature of QCD. Light hybrid states, which are subjects of the present study, have been intensively investigated in the framework of different theoretical methods such as lattice QCD [9, 10], the Schwinger-Dyson formalism [11–13],the flux tube model [14, 15], the MIT bag model [16, 17] and QCD Laplace sum-rules(LSRs) [18–34]. In particular, Ref. [21] contains a comprehensive LSRs analysis of the light hybrids for $J = 0$ and 1 with all the possible combinations for the parity and charge quantum numbers. Analyses show that the 0^{++}, 0^{--}, 1^{++}, and 1^{--} states are mainly stable, while 0^{+-}, 0^{-+}, 1^{+-}, and 1^{-+} quantum numbers lead to unstable and controversial results. Expected to be the lightest hybrid mesons, the ones with 1^{-+} have been the subject of much additional studies. In the QCD sum rules, predictions on the 1^{-+} light hybrid mesons are inconsistent among different works. For instance, I. I. Balitsky *et al*'s prediction of mass for 1^{-+} state is in the range, 1.0–1.3 GeV [18, 22], J . I. Latorre *et al* predicted the related mass to be around 2.1 GeV [24] and the obtained mass for 1^{-+} state is around 2.5 GeV in Refs. [19, 35, 36]. The mass of 1^{-+} was re-analyzed by including the quark-gluon condensates up to 8 dimensions [34] and it was found that the mass value increases to be in the range 1.72–2.60 GeV. The obtained mass range did not favor the $\pi_1(1400)$ and the $\pi_1(1600)$ to be pure hybrid states and suggests the $\pi_1(2015)$, observed by E852, to have much of a hybrid constituent. The masses of the light hybrid mesons with $J^{PC} = 1^{-+}$ quantum numbers have also been calculated using different theoretical methods other than QCD sum rules [37–40].

Concerning other quantum numbers, the masses of the 0^{++} and 0^{-+} light hybrid mesons were calculated using the QCD sum rule method by considering two kinds of the interpolated currents with the same quantum numbers. While the approximately equal mass was predicted for the 0^{-+} hybrid states from the two different currents, different masses were obtained for the 0^{++} hybrid

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Neutrino Mixing and Resonant Leptogenesis in Inverse Seesaw and $\Delta(54)$ Flavor Symmetry

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Abstract

The current work involves augmenting the $\Delta(54)$ discrete flavor model by incorporating two Standard Model Higgs particles into the Inverse Seesaw mechanism. We introduced Weyl fermions and Vector like fermions, which are gauge singlets in the Standard Model and produces Majorana mass terms in our lagrangian. The resulting mass matrix deviates from the tribimaximal neutrino mixing pattern producing a non-zero reactor angle (θ_{13}) . We have determined the effective Majorana neutrino mass, which is the parameter of relevance in neutrinoless double beta decay investigations, using the model's limited six-dimensional parameter space. We additionally investigate the possibility of baryogenesis in the proposed framework via resonant leptogenesis. We have the non-zero value for resonantly enhanced CP asymmetry originating from the decay of right-handed neutrinos at the TeV scale, accounting for flavor effects. The evolution of lepton asymmetry is systematically analyzed by numerically solving a set of Boltzmann equations, leading to the determination of the baryon asymmetry with a magnitude of $|\eta_B| \approx 6 \times 10^{-10}$. This outcome is achieved by selecting specific values for the right-handed neutrino mass $M_1 = 10$ TeV and mass splitting, $d \approx 10^{-8}$.

Keywords— Majorana neutrinos, Double inverse seesaw, Jarlskog invariant, Tribimaximal neutrino mixing, Neutrinoless double-beta decay

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Revealing the nature of Ω_c-like states from pentaquark perspective

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We systematically study the electromagnetic properties of controversial states whose internal structure is not elucidated and we try to offer a different point of view to unravel the internal structure of these states. Inspired by the Ω_c states observed by the LHCb Collaboration, we study the electromagnetic properties of the Ω_c-like states as the compact diquark-diquark-antiquark pentaquarks with both $J^P = \frac{1}{2}^-$ and $J^P = \frac{3}{2}^-$ in the context of the QCD light-cone sum rule model. From the obtained numerical results, we conclude that the magnetic dipole moments of the Ω_c-like states can reflect their inner structures, which can be used to distinguish their spin-parity quantum numbers. Measuring the magnetic moment of the Ω_c-like states in future experimental facilities can be very helpful for understanding the internal organization and identifying the quantum numbers of these states.

Keywords: Electromagnetic form factors, diquark-diquark-antiquark picture, QCD light-cone sum rules, magnetic dipole moments

I. MOTIVATION

Many heavy baryon states have been discovered in recent years by experimental collaborations. One of the main challenges in non-perturbative QCD is to understand and shed light on the precise nature of these states. Through further theoretical explorations involving the study of hadrons comprising a single heavy quark, it offers an exquisite basis to probe the dynamics of a light diquark in a heavy quark background, to enhance the understanding of the non-perturbative nature of QCD, and to test the predictions of different phenomenological models. In recent decades, there have been significant experimental advancements in the field of singly-charm/bottom baryons, resulting in a dramatic increase in the number of particles [1–30]. As the data for the presence of some of these states is scarce and their internal structure, as well as quantum numbers, are not well defined, additional experimental exploration is therefore required. Therefore, researchers in hadron physics continue to study these topics through theoretical and experimental research, as they have not yet been fully understood.

In 2017, the LHCb collaboration studied the $\Xi_c^+ K^-$ mass spectrum and observed five new narrow excited Ω_c states, $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$, $\Omega_c(3090)$, $\Omega_c(3119)$ [22]. The parameters that have been measured are as follows

$$\begin{aligned}
M_{\Omega_c(3000)} &= 3000.4 \pm 0.2 \pm 0.1 \text{ MeV}, \quad \Gamma_{\Omega_c(3000)} = 4.5 \pm 0.6 \pm 0.3 \text{ MeV},\\
M_{\Omega_c(3050)} &= 3050.2 \pm 0.1 \pm 0.1 \text{ MeV}, \quad \Gamma_{\Omega_c(3050)} = 0.8 \pm 0.2 \pm 0.1 \text{ MeV},\\
M_{\Omega_c(3066)} &= 3065.6 \pm 0.1 \pm 0.3 \text{ MeV}, \quad \Gamma_{\Omega_c(3066)} = 3.5 \pm 0.4 \pm 0.2 \text{ MeV},\\
M_{\Omega_c(3090)} &= 3090.2 \pm 0.3 \pm 0.5 \text{ MeV}, \quad \Gamma_{\Omega_c(3090)} = 8.7 \pm 1.0 \pm 0.8 \text{ MeV},\\
M_{\Omega_c(3119)} &= 3119.1 \pm 0.3 \pm 0.9 \text{ MeV}, \quad \Gamma_{\Omega_c(3119)} = 1.1 \pm 0.8 \pm 0.4 \text{ MeV}. \qquad (1)
\end{aligned}$$

Later, the former four states $\Omega_c(3000)$, $\Omega_c(3050)$, $\Omega_c(3066)$ and $\Omega_c(3090)$ were confirmed by the LHCb and Belle Collaborations [31, 32]. The discovery of the LHCb collaboration has led to a new experimental situation, which requires a more detailed study of heavy baryons and their properties. The discovery of these states, although their quantum numbers have not been determined, could provide new insights into QCD and its complex behavior. This could lead to a deeper understanding of the underlying properties of QCD. However, our information about their properties is still not sufficient and further suggestions for experimental exploration of Ω_c-like states should be addressed. The experimental discoveries were followed by various theoretical studies, investigating them in the conventional baryon, molecular, and compact pentaquark states to shed light on their exact nature and quantum numbers (for details see the Refs. [33–37]).

The literature review indicates that the majority of research has concentrated on computing the spectroscopic and decay parameters of these states. However, it is evident that relying exclusively on spectroscopic and decay

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Beauty-charm Meson Family with Coupled Channel Effects and Their Strong Decays

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We systematically calculate the spectrum and hadronic decays of the beauty-charm system in a coupled channel framework. The unquenched effects are induced by the $^3P_0$ model. Our results can good explain the observed B_c meson spectrum. For the coupled channel components, we predicted the $1S$ is about 4%, the $2S$, $1P$, $2P$, $1D$, and $2D$ states are about 14%, 10%, 33%, and 17% respectively. For the $3S$, $2P$ and $2D$ states, the strong decay is allowed, The hadronic decay widths of the 3^1S_0, 3^3S_1, 2^3P_2 states are about 110 MeV, 69 MeV, and 3 MeV, respectively. While the decay widths of the 2^3D_1, $2D$, $2D'$, and 2^3D_2 states are 60 MeV, 149 MeV, 65 MeV, and 72 MeV, respectively.

I. INTRODUCTION

The understanding of hadron structures and their transitions at Fermi scale is fundamental issue from both the theoretical and experimental aspects in Particle Physics. For the conventional meson spectrum composed of a quark and an antiquark, the beauty-charm meson family is relatively incomplete. Up to now, only three beauty-charm mesons have been observed in experiments, i.e, the $B_c(1S)$, the $B_c(2S)$ and $B_c^*(2S)$.

The ground state $B_c(1^1S_0)$ of beauty-charm family was first discovered in 1998 by CDF at Fermilab [1]. The latest average mass for this state is $6274.47 \pm 0.27 \pm 0.17$ MeV [2]. One of the radial excited beauty-charm states was first discovered in $B_c^+\pi^+\pi^-$ invariant mass spectrum with subprocess $B_c^+ \to J/\psi\pi^+$ using the sample corresponding to 4.9 fb^{-1} of 7 TeV and 19.2 fb^{-1} of 8 TeV pp collision data collected by the ATLAS experiment at the LHC in 2014 [3]. After that, two excited beauty-charm states $B_c(2^1S_0)$ and $B_c^*(2^3S_1)$ instead of one peak are discovered in $B_c^+\pi^+\pi^-$ invariant mass spectrum from both the CMS and LHCb experiments [4, 5]. The combined average mass for the $B_c(2^1S_0)$ is determined as 6871.2 ± 0.1 MeV [2]. For the vector excited state, $B_c^*(2^3S_1)$ first decays via hadronic transition $B_c^{*+}(2^3S_1) \to B_c^{*+}(1^3S_1)\pi^+\pi^-$, and then the vector $B_c^{*+}(1^3S_1)$ decays via electromagnetic transition $B_c^{*+}(1^3S_1) \to B_c^+(1^1S_0) + \gamma$. However, the radiated photon is soft with energy around 60MeV, which is not reconstructed in both the CMS and LHCb experiments. Thus the value of the mass of $B_c^{*+}(2^3S_1)$ relies on the precise information of $B_c^{*+}(1^3S_1)$. On the other hand, other beauty-charm meson states including orbitally excited states are not observed at experiments yet.

In theoretical aspects, the mass spectra of beauty-charm mesons have been studied by many groups. For example, the quark potential models [6–15], QCD sum rule [16–20], the heavy quark effective theory [21], and the Dyson-Schwinger equation approach of QCD [22, 23]. Besides, the properties of the low-lying B_c mesons are also investigated in the lattice QCD based on the first principles [24–26].

The quark potential models in Refs. [6–12, 14] are usually called quenched quark models. In quenched quark models, the convention mesons are constituted by a quark and an untiquark, and the mass spectrum comes from the interactions between constituent quarks. Therein the Godfrey-Isgur relativistic quark model [14] is usu-

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B-mesons as essential probes of hot QCD matter

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Abstract

This article elucidates the pivotal role of b-mesons and bottomonium states in exploring the existence and properties of hot QCD matter (commonly known as quark-gluon-plasma (QGP) produced within the crucible heavy-ion collision experiments). Owing to the complex and confounding nature of strong interaction force the direct detection of probing the hot QCD matter is not feasible. In light of this, investigating the dynamics of b-quarks and anti-quarks within the hot QCD medium emerges as an invaluable indirect probe. The impact of b-quarks and the mesons spans a spectrum of interesting domains regarding the physics of QCD at finite temperature, encompassing the QCD phase transition, color screening, quarkonia dissociation, heavy quark energy loss and collective flow, anisotropic aspects, and strongly coupled nature of hot QCD medium. These aspects underscore the indispensable nature of B-mesons in the quest to create and explore the complex nature of strong interaction force through the QGP/hot QCD matter. In this context, we mainly focus on works related to transport studies of b-mesons in hot QCD medium, lattice QCD, and effective field theory studies on bottomonium states, and finally, open quantum system frameworks to quarkonia to explore the properties of hot QCD medium in relativistic heavy-ion collision experiments.

Keywords: B-mesons, heavy-quark dynamics, hot QCD medium, lattice QCD

QCD at Finite Temperature and Density - Equation of State

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Abstract. As an important set of thermodynamic quantities, knowledge of the equation of state over a broad range of temperatures and chemical potentials in the QCD phase diagram is crucial for our understanding of strongly-interacting matter. There is a good understanding from first-principles results in lattice QCD, perturbative QCD and chiral effective field theory about the equation of state. However, these approaches are valid in different regimes of the phase diagram, and therefore, a method of providing an equation of state that covers a full range of the phase diagram involves matching together these results with appropriate models in order to fill in the gaps between these regions. Furthermore, with such equations of state, important questions about QCD phase structure can begin to be addressed, such as whether there is a critical point in the QCD phase diagram. In this contribution to the proceedings, equations of state from first-principles and effective theories will be discussed in order to understand how QCD thermodynamics is affected by the presence of a critical point.

1 Introduction

The phase structure of strongly-interacting matter has been a focus of efforts for both the theoretical and experimental communities for decades. Upon exploration of the QCD phase diagram, the question being probed is how does strongly-interacting matter respond to heat, i.e. increasing temperature, and compression, i.e. increasing density. Therefore, the QCD equation of state (EoS) is the object of study lending from the fact that these are thermodynamic properties. First-priniciples lattice QCD calculations have given insight into the zero and low-to-moderate density equation of state [1–5]. Also from the lattice with good precision, the transition temperature at vanishing chemical potential has been calculated as well as the curvature of the transition line and where it lies up to $\mu_B \simeq 2.5T$ [6, 7]. In the low-temperature region of the QCD phase diagram, the system is rather well-described by an ideal gas of hadrons and their resonances [8–11]. However, as the density, or equivalently chemical potential, increases, nuclear matter exhibits a liquid-gas phase transition in the low temperature regime that is described by an interacting van der Waals equation of state [9]. Furthermore, chiral effective field theory is the appropriate low energy theory that covers the low-temperature and low-to-moderate-density regime [12]. On the other hand, at asymptotically high temperatures and densities, perturbative QCD (pQCD) results yield access to the asymptotic regime of the QCD phase diagram [13–15]. From the perspective of connecting to the observable universe, zero temperature calculations from chiral effective field theory and pQCD can be combined with astrophysical constraints to learn about the QCD equation

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The Path to N^{3}LO Parton Distributions

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This paper is dedicated to the memory of Stefano Catani,
Grand Master of QCD, great scientist and human being

Abstract

We extend the existing leading (LO), next-to-leading (NLO), and next-to-next-to-leading order (NNLO) NNPDF4.0 sets of parton distribution functions (PDFs) to approximate next-to-next-to-next-to-leading order (aN^{3}LO). We construct an approximation to the N^{3}LO splitting functions that includes all available partial information from both fixed-order computations and from small and large x resummation, and estimate the uncertainty on this approximation by varying the set of basis functions used to construct the approximation. We include known N^{3}LO corrections to deep-inelastic scattering structure functions and extend the FONLL general-mass scheme to $\mathcal{O}\left(\alpha_s^3\right)$ accuracy. We determine a set of aN^{3}LO PDFs by accounting both for the uncertainty on splitting functions due to the incomplete knowledge of N^{3}LO terms, and to the uncertainty related to missing higher corrections (MHOU), estimated by scale variation, through a theory covariance matrix formalism. We assess the perturbative stability of the resulting PDFs, we study the impact of MHOUs on them, and we compare our results to the aN^{3}LO PDFs from the MSHT group. We examine the phenomenological impact of aN^{3}LO corrections on parton luminosities at the LHC, and give a first assessment of the impact of aN^{3}LO PDFs on the Higgs and Drell-Yan total production cross-sections. We find that the aN^{3}LO NNPDF4.0 PDFs are consistent within uncertainties with their NNLO counterparts, that they improve the description of the global dataset and the perturbative convergence of Higgs and Drell-Yan cross-sections, and that MHOUs on PDFs decrease substantially with the increase of perturbative order.

Light quark mediated Higgs boson production in association with a jet at the next-to-next-leading order and beyond

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Abstract: We study the light quark effect on the Higgs boson production in association with a jet at the LHC in the intermediate transverse momentum region between the quark and the Higgs boson mass scales. Though the effect is suppressed by the small Yukawa coupling, it is enhanced by large logarithms of the quark mass ratio to the Higgs boson mass or transverse momentum. Following a remarkable success of the logarithmic expansion [39] for the prediction of the next-to-next-to-leading bottom quark contribution to the total cross section of the Higgs boson production we extend the analysis to its kinematical distributions. A new factorization formula is derived for the light quark mediated $gg \to Hg$ amplitudes and the differential cross section of the process is computed in the logarithmic approximation, which is used for an estimate of the bottom quark effect at the next-to-next-to-leading order.