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The QCD θ-parameter in canonical quantization

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Abstract

The role of the QCD θ-parameter is investigated in pure Yang–Mills theory in the spacetime given by the four-dimensional Euclidean torus. While in this setting the introduction of possibly unphysical boundary conditions is avoided, it must be specified how the sum over the topological sectors is to be carried out. To connect with observables in real time, we perceive the partition function as the trace over the canonical density matrix. The system then corresponds to one of a finite temperature on a spatial three-torus. Carrying out the trace operation requires canonical quantization and gauge fixing. Fixing the gauge and demanding that the Hermiticity of the Hamiltonian is maintained leads to a restriction of the Hilbert space of physical wave functionals that generalizes the constraints derived from imposing Gauß' law. Consequently, we find that the states in the Hilbert space are properly normalizable under an inner product that integrates over each physical configuration represented by the gauge potential one time and one time only. The observables derived from the constrained Hilbert space do not violate charge-parity symmetry. We note that an exact hidden symmetry of the theory that is present for arbitrary values of θ in the Hamiltonian is effectively promoted to parity conservation in this constrained space. These results, derived on a torus in order to avoid the introduction of boundary conditions, also carry over to Minkowski spacetime when taking account of all possible gauge transformations.

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Numerical challenges for energy conservation in N-body simulations of collapsing self-interacting dark matter haloes

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ABSTRACT

Context. Dark matter (DM) haloes can be subject to gravothermal collapse if DM is not collisionless but has strong self-interactions. When the scattering is capable of efficiently transferring heat from the centre to the outskirts, the central region of the halo collapses and can reach densities much higher than those for collisionless DM. This phenomenon is potentially observable in studies of strong lensing. Current theoretical efforts are motivated by observations of surprisingly dense substructures. However, a comparison with observations requires accurate predictions. One method to obtain such predictions is to use N-body simulations. The collapsed haloes are extreme systems that pose severe challenges to state-of-the-art codes used in the field of self-interacting dark matter (SIDM).
Aims. In this work, we investigate the root of such problems with a focus on energy non-conservation. Moreover, we discuss strategies to avoid them.
Methods. We run N-body simulations with and without DM self-interactions of an isolated DM-only halo and change numerical parameters relevant to the accuracy of the simulation.
Results. We find that not only the numerical scheme for the DM self-interactions can lead to energy non-conservation but also the modelling of gravitational interaction and the time integration are problematic. The issues we found are: (a) particles changing their time step in a non-time-reversible manner; (b) the asymmetry in the tree-based gravitational force evaluation; (c) SIDM velocity kicks break the symplectic nature and time symmetry.
Conclusions. In principle, tuning the parameters of the simulation to achieve a high accuracy allows for conserving energy not only at early stages of the evolution but also at late ones. However, the cost of the simulations becomes prohibitively large. Some of the problems making the simulations of the gravothermal collapse phase inaccurate, can be overcome by choosing appropriate numerical schemes. However, others remain challenging. Our findings motivate further work on addressing the challenges in simulating strong dark matter self-interactions.

Key words. methods: numerical — dark matter

1. Introduction

Self-interacting dark matter (SIDM) is an alternative scenario to the collisionless cold dark matter (CDM) of the standard cosmological model, and it was originally proposed by Spergel & Steinhardt (2000) to address problems on small scales, i.e. galactic scales (for a review of small-scale problems see Bullock & Boylan-Kolchin 2017). Various signatures of dark matter (DM) scatterings are explored, e.g. the formation of density cores (e.g. Mastromarino et al. 2023), rounder halo shapes (e.g. Gonzalez et al. 2024) or DM–galaxy offsets in mergers of galaxy clusters (e.g. Sabarish et al. 2023). These features allow for constraining the particle physics properties of DM (e.g. Gopika & Desai 2023; Zhang et al. 2024; Wittman et al. 2023). For a review of SIDM, we refer the reader to Tulin & Yu (2018) and Adhikari et al. (2022).

Observations of surprisingly dense substructures (e.g. Vegetti et al. 2010; Meneghetti et al. 2020; Minor et al. 2021; Granata et al. 2022) motivate SIDM studies with relatively large cross-sections at low velocities. Potentially such models can explain objects denser than expected from CDM (e.g. Yang & Yu 2021; Nadler et al. 2023; Yang et al. 2023; Zeng et al. 2023). An SIDM halo can collapse due to an effective heat outflow arising from the self-interactions. When a system bound by self-gravity loses energy it becomes more compact and its velocity dispersion in the centre increases, i.e. it becomes hotter. This enhances the energy outflow even more. The gravothermal evolution of a self-gravitating system is well known from globular clusters (e.g. Lynden-Bell & Eggleton 1980). However, making accurate predictions by modelling the late stages of the collapse of SIDM haloes is challenging as we discuss in this paper.

N-body simulations provide a crucial way of making SIDM predictions and probing the available parameter space for SIDM models. Burkert (2000) developed the first SIDM simulation of that kind, which employs a Monte Carlo scheme. Further implementations of this scheme were followed (e.g. Kochanek & White 2000; Davé et al. 2001; Colin et al. 2002). The simulation techniques for SIDM have evolved since then. But all modern SIDM codes rely on a Monte Carlo scheme with the notable exception of Huo et al. (2020). Vogelsberger et al. (2012) and Rocha et al. (2013) largely improved the estimate of the scattering probability by using the actual phase space distribution.

Nonperturbative Collins-Soper Kernel from Chiral Quarks with Physical Masses

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Abstract

We present a lattice QCD calculation of the rapidity anomalous dimension of quark transverse-momentum-dependent distributions, i.e., the Collins-Soper (CS) kernel, up to transverse separations of about 1 fm. This unitary lattice calculation is conducted, for the first time, employing the chiral-symmetry-preserving domain wall fermion discretization and physical values of light and strange quark masses. The CS kernel is extracted from the ratios of pion quasi-transverse-momentum-dependent wave functions (quasi-TMDWFs) at next-to-leading logarithmic perturbative accuracy. Also for the first time, we utilize the recently proposed Coulomb-gauge-fixed quasi-TMDWF correlator without a Wilson line. We observe significantly slower signal decay with increasing quark separations compared to the established gauge-invariant method with a staple-shaped Wilson line. This enables us to determine the CS kernel at large nonperturbative transverse separations and find its near-linear dependence on the latter. Our result is consistent with the recent lattice calculation using gauge-invariant quasi-TMDWFs, and agrees with various recent phenomenological parametrizations of experimental data.

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Gravitational waves in a cyclic Universe: resilience through cycles and vacuum state

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We present a generalised calculation for the spectrum of primordial tensor perturbations in a cyclic Universe, making no assumptions about the vacuum state of the theory and accounting for the contribution of tensor modes produced in the dark energy phase of the previous cycle. We show that these modes have minimal impact on the spectrum observed in the current cycle, except for corrections on scales as large as the comoving Hubble radius today. These corrections are due to sub-horizon modes produced towards the end of the dark energy phase, persisting into the *ekpyrotic* phase of the next cycle as additional quanta. In relation to the vacuum state, we argue that non-Bunch-Davies quanta can easily overwhelm the energy density driving the dark energy phase, potentially compromising the model. Therefore, avoiding backreaction effects sets restrictive constraints on deviations away from the Bunch-Davies vacuum during this phase, limiting the overall freedom to consider alternative vacua in the cyclic Universe.

I. INTRODUCTION

The most compelling observational evidence supporting cosmological inflation [1–4] as the leading theory of the early Universe is currently provided by the Planck satellite measurement of the spectral index of scalar perturbations, $n_s = 0.9649 \pm 0.0042$ [5]. In the simplest single-field slow-roll inflationary models, the spectrum of scalar modes is expected to be almost but not exactly flat [6–9], with deviations from flatness are quantified in terms of how much n_s deviates from 1 [10–13]. As a result, the Planck data seem to be in excellent agreement with the theoretical predictions of inflationary models [5, 14], ruling out a Harrison-Zeldovich scale-invariant spectrum [15–17] (corresponding to $n_s = 1$) at a statistical level exceeding 8.5 standard deviations and lending weight to the inflationary paradigm.

That being said, with no aim to downplay the significance of this result or its interpretation, it is crucial to emphasise that, on its own, it does not provide conclusive evidence for cosmological inflation. Even hinging on a certain level of optimism and setting aside the uncertainty surrounding constraints on n_s from CMB experiments other than Planck[1] – or the potential implications arising from the well-known tensions [27–31] characterising the recent debate[2] – alternative theoretical mechanisms have been put forth, yielding an almost scale-invariant spectrum of primordial density fluctuations without invoking inflation.

An illustrative example of such mechanisms is the cyclic Universe [43–49] that, in contrast to the conventional cosmological framework, suggests a periodic history for the Cosmos. The model has been extensively studied and discussed in relation to a broad range of topics, including quantum gravity, modified gravity, gravitational waves and dark energy, see e.g., Refs. [50–83] or Refs. [84, 85] for reviews. In broad terms, each cycle comprises a phase recasting the standard Hot Big Bang theory (during which large-scale structures take shape), followed by a phase of slow, accelerated expansion mirroring the present-day observational evidence for a Dark Energy dominated dynamics. In the cyclic Universe, this latter stage also serves to dilute inhomogeneities and flatten the spatial geometry. Subsequently, a contraction phase ensues, generating nearly scale-invariant density perturbations. Finally, the cycle concludes with a big-crunch/big-bang transition, during which matter and radiation are generated, setting the stage for the next cycle.

Notice that both inflation and the cyclic Universe provide physical mechanisms to produce an almost scale-invariant spectrum of density perturbations [86–88]. In addition, they can both explain observational facts such as the homogeneity in the cosmic microwave background (CMB) radiation [89] and the fact that the present-day spatial geometry of the Universe appears to be flat, or at the very least nearly flat[3]. Therefore, at first glance, one might wonder how to distinguish between the two models. Focusing solely on scalar modes, this is a challenging knot to unravel [111, 112]. However, the two scenarios yield significantly distinct predictions for the stochastic background of gravitational waves [50]. Similar to scalar modes, inflation predicts a nearly scale-invariant (red-tilted) spectrum of tensor modes [12, 13, 113]. Conversely, in the cyclic Universe, the tensor spectrum is typically blue-tilted, and its amplitude is many orders of magnitude lower than that predicted by inflation, remaining well below any observable threshold achievable in the near future. Consequently, any measurement of primordial gravitational waves (e.g., through the effects left in the CMB B-mode polarisation at large angular scales) would offer conclusive evidence for inflation, discounting the cyclic model.

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[1] Over the years, constraints on the spectral index have been released by a multitude of Planck-independent CMB experiments such as WMAP [18, 19], the Atacama Cosmology Telescope (ACT) [20, 21], and the South Pole Telescope (SPT) [22, 23]. When considering these data at face value, Planck is currently the only experiment excluding $n_s = 1$ at a statistical significance much larger than 3σ. Conversely, ACT shows a preference for $n_s = 1$ [21, 24]. Different combinations of these data overall support the result $n_s \neq 1$, although sometimes they lead to discordant results in terms of the other inflationary parameters or the preferred inflationary models [25, 26].

[2] For studies suggesting potential implications of cosmological tensions for inflation, see, e.g., Refs. [32–42]

[3] For recent discussions surrounding the spatial geometry of the Universe, see, e.g., [90–110]

Neural Simulation-Based Inference of the Neutron Star Equation of State directly from Telescope Spectra

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Neutron stars provide a unique opportunity to study strongly interacting matter under extreme density conditions. The intricacies of matter inside neutron stars and their equation of state are not directly visible, but determine bulk properties, such as mass and radius, which affect the star's thermal X-ray emissions. However, the telescope spectra of these emissions are also affected by the stellar distance, hydrogen column, and effective surface temperature, which are not always well-constrained. Uncertainties on these nuisance parameters must be accounted for when making a robust estimation of the equation of state. In this study, we develop a novel methodology that, for the first time, can infer the full posterior distribution of both the equation of state and nuisance parameters directly from telescope observations. This method relies on the use of neural likelihood estimation, in which normalizing flows use samples of simulated telescope data to learn the likelihood of the neutron star spectra as a function of these parameters, coupled with Hamiltonian Monte Carlo methods to efficiently sample from the corresponding posterior distribution. Our approach surpasses the accuracy of previous methods, improves the interpretability of the results by providing access to the full posterior distribution, and naturally scales to a growing number of neutron star observations expected in the coming years.

CONTENTS

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Angular bispectrum and trispectrum of scalar-induced gravitational-waves: all contributions from primordial non-Gaussianity $f_{\rm NL}$ and $g_{\rm NL}$

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Studying the primordial non-Gaussianity of inflationary perturbations is crucial for testing the inflation paradigm of the early universe. In this work, we conduct a comprehensive analysis of the angular bispectrum and trispectrum of scalar-induced gravitational waves (SIGWs) in the presence of local-type primordial non-Gaussianity parameterized by $f_{\rm NL}$ and $g_{\rm NL}$, deriving their semi-analytical formulae for the first time. Our findings indicate that it is the presence of primordial non-Gaussianity that leads to a non-Gaussian SIGW background, suggesting that the angular bispectrum and trispectrum of SIGWs could serve as probes of the primordial non-Gaussianity. Our numerical results further illustrate that $f_{\rm NL}$ and $g_{\rm NL}$ exert significant impacts on the spectral amplitudes, potentially reaching up to 10^{-5} for the former and 10^{-8} for the latter. In particular, we demonstrate that the angular bispectrum and trispectrum exhibit characteristic dependence on the angular multipoles and frequency bands. They hold potentials to be measured by gravitational-wave detectors that may advance our understanding of the origin of the universe.

I. INTRODUCTION

Primordial non-Gaussianity stands for the deviation from Gaussian distribution of the primordial curvature perturbations, thus characterizing the dynamics of the early universe during inflation [1–7]. Though the standard inflation paradigm predicts the nearly Gaussian perturbations [8, 9], many other inflation models hold no brief for this prediction [10]. In particular, the primordial bispectrum is characterized by an amplitude parameter $f_{\rm NL}$, while the primordial trispectrum by $g_{\rm NL}$ and so on [11]. Constraints on the primordial non-Gaussianity have been obtained through observations of cosmic microwave background (CMB) [12] and large-scale structure (LSS) [13, 14]. However, these observations are only responsive to the cosmological perturbations on large scales that are comparable to the overall observational patch of the universe, leaving the perturbations on smaller scales to be insensitive. Since modes of smaller wavelength reentered the horizon earlier, the universe before the last-scattering surface would have been opaque to the electromagnetic probes [15]. Therefore, to conquer the above challenge, it is necessary to develop alternative probes that can effectively convey information from the early universe to our detectors. Given that Einstein's general relativity predicts that gravitational waves (GWs) propagate without dissipation [16, 17], we expect them to be a valuable new messenger of the early universe on small scales, in contrast to the traditional observations such as CMB and LSS on large scales.

The scalar-induced gravitational waves (SIGWs) are sensitive to the local-type primordial non-Gaussianity on small scales, making them potential indicators of this non-Gaussianity. Theoretically, they were produced through non-linear processes by the linear inflationary perturbations that reentered the Hubble horizon in the early universe [18–24]. Taking into account $f_{\rm NL}$ and $g_{\rm NL}$ can lead to significant alterations by several orders of magnitude in both the energy-density fraction spectrum and the angular power spectrum [25], especially within the projected sensitivity regimes of future or futuristic gravitational-wave detection programs [26–50]. This suggests the potential for measuring primordial non-Gaussianity through the search for an anisotropic SIGW background. Other related works can be found in Refs. [51–69] and Refs. [70–72], respectively. Additionally, in conjunction with the production of scalar-induced gravitational waves, these scalar perturbations may gravitationally collapse into primordial black holes

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The Odd 2D Bubbles, 4D Triangles, and Einstein and Weyl Anomalies in 2D Gravitational Fermionic amplitudes: The Role of Breaking Integration Linearity for Anomalies

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Doctoral Thesis

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Abstract

We investigated Relations Among Green Functions defined in the context of an alternative strategy for coping with the divergences, also called the Implicit Regularization Method (IREG). This procedure does not use specific rules for the context being investigated: the mathematical content (divergent and finite) will remain intact until the calculations end. The divergent part will be organized through standardized objects free of physical quantities. In contrast, the finite part is projected in a class of well-behaved functions that carry all the amplitudes' physical content. That relations arise in fermionic amplitudes in even space-time dimensions, where anomalous tensors connect to finite amplitudes as in the bubbles and triangles in two and four dimensions. Those tensors depend on surface terms, whose non-zero values arise from finite amplitudes as requirements of consistency with the linearity of integration and uniqueness. Maintaining these terms implies breaking momentum-space homogeneity and, in a later step, the Ward identities. Meanwhile, eliminating them allows more than one mathematical expression for the same amplitude. That is a consequence of choices related to the involved Dirac traces. Independently of divergences, it is impossible to satisfy all symmetry implications by simultaneously requiring vanishing surface terms and linearity. Then we approach the 1-loop level fermionic correction for the propagation of the graviton in a space-time $D = 1 + 1$ through the action of a Weyl fermion in curved space-time. In this context, gravitational anomalies arise, and the amplitudes investigated have the highest degree of divergence quadratic. That imposes a substantial algebraic effort; however, the conclusions are in agreement with the non-gravitational amplitudes. At the end of the calculations, we show how it is possible to fix the value of the divergent part through the relations imposed for amplitudes.

Keywords: Anomalies, Gravitational Anomalies, Divergences, Implicit Regularization.

Late-Time constraints on Interacting Dark Energy: Analysis independent of H_0, r_d and M_B

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A possible interaction between cold dark matter and dark energy, corresponding to a well-known interacting dark energy model discussed in the literature within the context of resolving the Hubble tension, has been investigated. We put constraints on it in a novel way, by creating new likelihoods with an analytical marginalization over the Hubble parameter H_0, the sound horizon r_d, and the supernova absolute magnitude M_B. Our aim is to investigate the impacts on the coupling parameter of the interacting model, ξ, and the equation of state of dark energy w and the matter density parameter $\Omega_{m,0}$. The late-time cosmological probes used in our analysis include the PantheonPlus (calibrated and uncalibrated), Cosmic Chronometers, and Baryon Acoustic Oscillations samples and the Pantheon for comparison. Through various combinations of these datasets, we demonstrate hints of up to 2σ deviation from the standard Λ cold dark matter model.

Keywords: Dark Energy; Dark Matter; Interaction; Cosmological parameters.

I. INTRODUCTION

Over the last few decades, cosmological measurements indicating an expanding universe with an acceleration have suggested that Einstein's General Theory of Relativity (GR) alone is probably not the ultimate theory of gravity capable of explaining all the available observational evidences. Observational data from Type Ia Supernovae (SNeIa) [1–3], Baryon Acoustic Oscillations (BAO) [4–7], and the Cosmic Microwave Background (CMB) [8] provided compelling evidence for the modifications either in the matter sector of the universe or in the gravitational sector. The simplest modification is the introduction of a positive cosmological constant, Λ, into the gravitational equations described by Einstein's GR [1, 2, 9–12] and the resulting picture – the so-called Λ-Cold Dark Matter (ΛCDM) cosmological model – has been found to be consistent with a wide range of observational datasets. Nevertheless, the ΛCDM model is now facing both theoretical and observational challenges [13–18]. Consequently, there has been growing momentum for a revision of ΛCDM cosmology in recent times [19–26]. Thus, the question arises: Is GR + Λ the fundamental theory of gravity, or merely an approximation of a more complete gravitational theory yet to be discovered? One natural avenue of exploration is to consider modified gravity theories, which show theoretical and observational promise in addressing the observed discrepancies. With the ever-increasing sensitivity and precision of present and upcoming astronomical surveys, modified gravity theories emerge as viable contenders alongside GR + Λ. The search for the ultimate answer in this direction is ongoing. According to the existing literature, we currently have a cluster of cosmological scenarios broadly classified into two categories: i) cosmological scenarios within GR, commonly known as dark energy models, and ii) cosmological scenarios beyond GR, commonly known as modified gravity models.

In this article, we focus on the first approach, which means that the gravitational sector of the universe is well described by GR, but the modifications in the matter fields are needed to explain the current accelerating phase and recent observational tensions and anomalies that persist in the structure of the standard cosmological model. The list of cosmological models in this particular domain is extensive, and here we are interested in investigating one of the generalized and appealing cosmological theories in which dark matter (DM) and dark energy (DE) interact with each other via an energy exchange mechanism between them. The theory of interacting DM-DE, widely known as IDE, has garnered massive attention in the community and has been extensively studied with many appealing results [27–63] (also see [63–65]). The IDE models gained prominence in modern cosmology for alleviating tensions in some key cosmological parameters

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Sudden breakdown of effective field theory near cool Kerr-Newman black holes

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Abstract: It was recently shown that (near-)extremal Kerr black holes are sensitive probes of small higher-derivative corrections to general relativity. In particular, these corrections produce diverging tidal forces on the horizon in the extremal limit. We show that adding a black hole charge makes this effect qualitatively stronger. Higher-derivative corrections to the Kerr-Newman solution produce tidal forces that scale inversely in the black hole temperature. We find that, unlike the Kerr case, for realistic values of the black hole charge large tidal forces can arise before quantum corrections due to the Schwarzian mode become important, so that the near-horizon behavior of the black hole is dictated by higher-derivative terms in the effective theory.

Mass Beyond Measure: Eccentric Searches for Black Hole Populations

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Stellar mass binary black holes of unknown formation mechanism have been observed, motivating new methods for distinguishing distinct black hole populations. This work explores how the orbital eccentricity of stellar mass binary black holes is a viable conduit for making such distinctions. Four different production mechanisms, and their corresponding eccentricity distributions, are studied in the context of an experimental landscape composed of mHz (LISA), dHz (DECIGO), and Hz (LIGO) range gravitational wave detectors. We expand on prior work considering these effects at fixed population eccentricity. We show that a strong signal corresponding to subsets of eccentric populations is effectively hidden from the mHz and dHz range gravitational wave detectors without the incorporation of high eccentricity waveform templates. Even with sufficiently large eccentricity templates, we find dHz range experiments with a LISA-like level of sensitivity are unlikely to aid in distinguishing different populations. We consider the degree to which a mHz range detector like LISA can differentiate among black hole populations independently and in concert with follow-up merger detection for binaries coalescing within a 10 year period. We find that mHz range detectors, with only $e < 0.01$ (nearly circular) sensitivity, can successfully discern eccentric sub-populations except when attempting to distinguish very low eccentricity distributions. In these cases where $e < 0.01$ sensitivity is insufficient, we find that the increase in event counts resulting from $e < 0.1$ sensitivity provides a statistically significant signal for discerning even these low eccentricity sub-populations. While improvements offered by $e < 0.1$ sensitivity can generally be increased by $\mathcal{O}(1)$ factors with $e < 0.4$ sensitivity, going beyond this in eccentricity sensitivity provides negligible enhancement.

CONTENTS

I. INTRODUCTION

The initial detection of stellar mass binary black hole pair (BBH) mergers by LIGO/VIRGO [1], since supplemented by numerous similar observations [2, 3], has ushered in an era of gravitational wave astronomy and suggests the existence of a sizeable BBH abundance. Our understanding of early Universe physics, the nature of dark matter, and especially astrophysical black hole production all stand to benefit from this data and must respond to the challenges presented by observed black holes of anomalous mass [4]. For these reasons, it is both timely and compelling to consider means by which we can infer the formation channels of the black holes we observe with gravitational wave detectors.

Various properties have been proposed as useful probes of the formation mechanisms of black holes, including black hole spin and mass [5–7]. This work investigates how the orbital eccentricity of BBH pairs can offer insight into black hole formation channels [8–15]. Prior work has

PROCEEDINGS OF SCIENCE

J/ψ−pair production at NLL in TMD factorisation at the LHC

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J/ψ−pair production at the LHC is currently one of the few tools available to probe gluon transverse momentum distributions (TMDs). In this context, data from LHCb in the collider mode have the potential to probe the evolution of the unpolarised-gluon TMDs and to measure the distribution of the linearly-polarised gluon in unpolarised protons for the first time. In this proceedings contribution, improved predictions obtained for the LHC (at $\sqrt{s} = 13$ TeV) up to next-to-leading logarithm (NLL) in TMD factorisation are presented. We show the obtained predictions of transverse-momentum distributions at different invariant masses and rapidities computed in the LHCb acceptance along with PDF uncertainty. We predict the azimuthal modulations of the cross section that arise from linearly-polarised gluons.

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1. Introduction

Inclusive J/ψ-pair production in proton-proton collisions represents a great tool to allow for extractions of the poorly known gluon Transverse Momentum Dependent Parton Distribution Functions (TMD-PDFs or TMDs) [1, 2]. Indeed, this process is mainly generated by gluon-gluon fusion and Color Singlet (CS) transitions are the main source of J/ψ pairs, for which TMD-factorisation-breaking effects are absent [3–5]. For this reason J/ψ-pair production is considered a great candidate for probing gluon TMDs at the LHC. Moreover, the invariant mass of the J/ψ-pair in the final state can be tuned with the individual momenta of the two J/ψ, allowing for the investigation of the scale evolution of the TMDs.

2. Overview of the process and formalism

The process considered in our study is the simultaneous production of two J/ψ in a single parton scattering from unpolarised proton-proton collisions. The J/ψ is relatively easy to produce and to detect, allowing for the collection of a large number of experimental data. From a theoretical point of view, though, it is ~~still not clear how to treat quarkonium p~~roduction: many models have been proposed in an attempt to describe quarkonium-production mechanisms. However, the consensus is that the *Colour-Singlet Model* (CSM) works for the particular case where a J/ψ-pair is generated [6].

A leading-order Feynman diagram of the process is shown in Figure 1. The protons have momentum P_1 and P_2 and the partons take a momentum fraction x_i from them (collinear contribution), besides having a transverse component k_{iT}. Considering the TMD factorisation [8], the non-perturbative gluon TMDs are defined through the hadron correlator $\Phi(x_i, k_{iT})$. For an

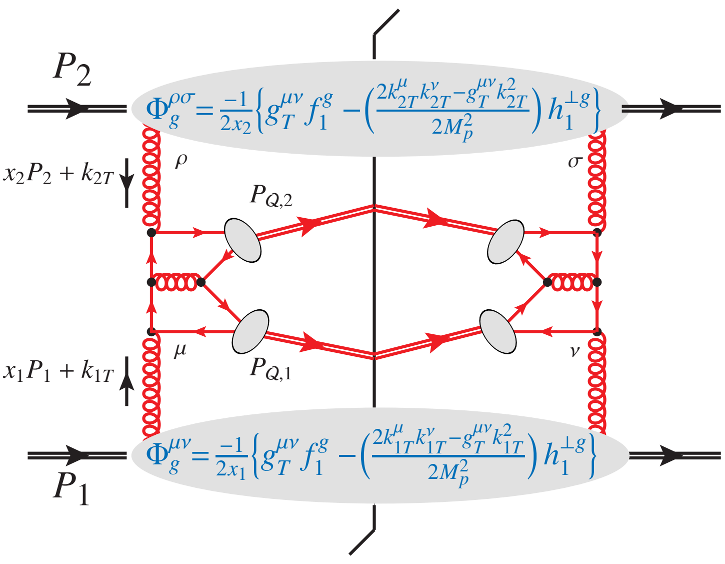

Figure 1: Schematic overview of the inclusive scattering for $p + p \to J/\psi + J/\psi$ in TMD factorisation. From [7].

Pseudoscalar Mesons and Emergent Mass

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Abstract

Despite its role in the continuing evolution of the Universe, only a small fraction of the mass of visible material can be attributed to the Higgs boson alone. The overwhelmingly dominant share may/should arise from the strong interactions that act in the heart of nuclear matter; namely, those described by quantum chromodynamics. This contribution describes how studying and explaining the attributes of pseudoscalar mesons can open an insightful window onto understanding the origin of mass in the Standard Model and how these insights inform our knowledge of hadron structure. The survey ranges over distribution amplitudes and functions, electromagnetic and gravitational form factors, light-front wave functions, and generalized parton distributions. Advances made using continuum Schwinger function methods and their relevance for experimental efforts are highlighted.

Hadron momentum spectra from analytical solutions of relativistic hydrodynamics

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We present analytical solution of relativistic hydrodynamics for a system having cylindrical symmetry with boost-invariant longitudinal expansion and Hubble-like transverse expansion. We also consider analytical solution for Hubble-like spherically expanding system. For these two cases, we calculate analytical expression for transverse momentum spectra of hadrons, at constant temperature freeze-out hypersurface using Cooper-Frye prescription. We compare our results for transverse momentum spectra with experimental results from Large Hadron Collider and CERN SPS where one expects cylindrical and spherical geometry of the fireball, respectively. In the case of low-energy collisions with spherical geometry, we calculate rapidity spectra and compare with the results from CERN SPS.

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I. INTRODUCTION

The earliest hydrodynamic approach for describing nucleus-nucleus collisions dates back to Landau's work in 1953, where he focused on longitudinal expansion along the collision axis [1]. Landau's non-dissipative expansion model provided an approximate analytical solution to ideal hydrodynamic equations, known as Landau hydrodynamics, resulting in Gaussian-like rapidity distributions of produced particles [1, 2]. Subsequent developments in hydrodynamics included the Hwa-Bjorken framework, proposing a boost-invariant scenario with a plateau-like rapidity distribution [3, 4]. However, the applicability of boost-invariance symmetry was limited to the mid-rapidity region in ultra-relativistic heavy-ion collisions. In contrast, the transverse-momentum (p_T) integrated yield across the entire rapidity region demonstrated an overall better agreement with the Gaussian structure suggested by Landau [2, 5–10]. Since Landau and Hwa-Bjorken solutions, several different forms of analytical solutions were proposed motivated by anticipated collective behaviour in relativistic heavy ion collisions [11–16]. Analytical solutions of relativistic hydrodynamics in simple symmetric cases are important because they serve as benchmarks for testing more realistic hydrodynamic simulation codes. In the last two decades, relativistic hydrodynamic simulations have been successfully applied to model the space-time evolution of the hot and dense matter produced at the Relativistic Heavy Ion Collider (RHIC) at BNL and the Large Hadron Collider (LHC) at CERN [17–31].

Majority of studies in hydrodynamic modelling of the evolution of hot and dense QCD matter, formed in relativistic heavy-ion collisions, rely on numerical simulations. The hydrodynamic evolution equations, comprising of energy-momentum and current conservation equations, are solved numerically with appropriate initial conditions. The conversion from hydrodynamic fields to the particle degree of freedom is achieved via the Cooper-Frye freeze-out prescription [32], which leads to the momentum distribution of observed hadrons. Semi-analytical framework of hydrodynamics-inspired phenomenological models provides another approach to study hadron momentum distribution [33–38]. Due to their simplicity, these phenomenological models have been employed extensively to analyze the momentum spectra of produced hadrons, offering insights into the properties of the strongly interacting matter at kinetic freeze-out [39–57]. These phenomenological models, like the Blast-wave model, primarily rely on the Cooper-Frye freezeout prescription with ad-hoc parameterization of fluid variables at the freeze-out hypersurface. While the parameterization of the fluid variables are inspired by hydrodynamic solutions, a direct correspondence between them has not yet been established. Therefore it would be highly beneficial to have a simple and fully analytical hydrodynamic framework for computation of hadron momentum distribution.

In this work, we obtain an analytical solution for relativistic hydrodynamics in a system characterized by cylindrical symmetry with boost-invariant longitudinal expansion and Hubble-like transverse expansion. Additionally, we explore an analytical solution for a Hubble-like spherically expanding system. These straightforward profiles allow us to derive a simple analytical solution for the temperature evolution relative to the proper time, facilitating a connection with the freeze-out hypersurface. For both cylindrical and spherical flow profiles, we compute the analytical expressions for the transverse momentum spectra of hadrons on a constant temperature freeze-out hypersurface, utilizing the Cooper-Frye prescription. We then compare these results for transverse momentum spectra with experimental findings from the Large Hadron Collider (LHC) and CERN SPS, where the fireball is expected to exhibit cylindrical and spherical

A Light-Front Model for the Transition Distribution Amplitudes for Backward Timelike Compton Scattering

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To access information on the internal structure of the nucleon, data from a variety of scattering experiments can be analyzed, in regimes where the information factorizes from an otherwise known scattering amplitude. A recent development, promising new insight, is the study of exclusive reactions in the backward kinematical region, where the information can be encoded in Transition Distribution Amplitudes (TDAs). We model the photon-to-nucleon TDAs, entering the factorized description of backward Timelike Compton Scattering, using techniques of light-front dynamics to integrate information from a quark model for the photon and the nucleon. We include the results of numerical predictions that could inform further experiments at Jefferson Lab and the future Electron–Ion Collider.

I. INTRODUCTION

Hard exclusive processes offer invaluable insight into unraveling the parton structure of hadrons. Notable examples include Deeply-Virtual Compton Scattering (DVCS) and its time-reversal conjugate process, Timelike Compton Scattering (TCS). The former is the scattering of a high-virtuality spacelike photon off a nucleon target, resulting in the production of a real photon and the recoiling nucleon, while the latter sees a real photon scatter off the nucleon target into a high-virtuality timelike photon. In the forward kinematical region, characterized by small absolute values of the Mandelstam variable t and large absolute values of the Mandelstam variable u, information on the internal structure of the nucleon is encoded in Generalized Parton Distributions (GPDs) [1–11]. These are related to matrix elements of a bilocal operator between the initial and final nucleon states, and represent the amplitude of transferring momentum to the hadron through the exchange of two partons.

The situation is more complex in the backward kinematical region, where $|u|$ is small and $|t|$ is large. However, the analogy with forward DVCS and TCS suggests a description in terms of a soft amplitude factorized from the hard scattering of the partons with the probe. The variable u characterizes the transition between a real photon and a nucleon, which can be encoded in Transition Distribution Amplitudes (TDAs) [12, 13]. These are related to matrix elements of a trilocal operator between the photon and nucleon states, and represent the amplitude of transferring momentum and one unit of baryon number through the exchange of three partons.

The focus of the present work is on backward TCS, which remains relatively unexplored compared to other processes involving TDAs [14–18]. The experimental study of TCS is a recent development, with data published for the first time in 2021 by the CLAS collaboration at Jefferson Lab for the forward region [19]. Moreover, backward TCS is expecially appealing, since the electromagnetic Bethe–Heitler background, where the initial photon directly couples to a lepton–antilepton pair in the final state, is significantly suppressed (except for very narrow regions of solid angle for the produced lepton) [13]. To compare the factorized description against experimental results and to guide further phenomenological studies, a model for the photon-to-nucleon TDAs is required, beginning with the leading contributions.

The model developed in this work is based on the framework of light-front dynamics (LFD) [20–23], where the interacting particles are described in the Fock space in terms of light-front wave functions (LFWFs). In Sec. II, the backward kinematical region of TCS is analyzed, and the factorized description of the scattering amplitude is introduced. The photon-to-nucleon TDAs are defined, and their expressions in terms of matrix elements of a trilocal operator between the initial photon and the final nucleon states are derived. Section III is dedicated to modelling the photon-to-nucleon TDAs, specifically in the support region where the description in terms of the leading Fock-components of the photon and nucleon LFWFs is suitable. The photon is treated as a light quark–antiquark pair, while the Fock representation of the nucleon is truncated to the three valence quarks in a constituent quark model that has already been applied to GPDs [24–29] and to nucleon-to-neutral-pion TDAs [18]. Given the impracticality of

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Neutrino phenomenology in the modular S_3 seesaw model

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We have studied neutrino phenomenology in the supersymmetric type-I seesaw model endowed with the $\Gamma_2 \simeq S_3$ modular symmetry. We have identified different realizations of the S_3 modular symmetry, referred to as models A, B, C, and D. The 4 models are compatible with neutrino mass being inverted ordering (IO). Moreover, models A, B, and D can also accommodate normal ordering (NO) neutrino masses. We identify parameter space for each model compatible with neutrino oscillation at the 2-σ level. We then proceed to study the neutrino phenomenology of each model. We find that the lightest neutrino mass can be as light as 0.64 meV in the case of NO in model A and 50 meV in the case of IO in model D. The smallest effective electron neutrino mass attainable in our analysis is 8.8 meV in the case of NO (model A), and 50 meV for IO (model D). Finally, we note that the effective Majorana mass can be as small as 0.33 meV in the case of NO (model A) and 22 meV for IO (model D).

I. INTRODUCTION

The Standard Model (SM) initially posited neutrinos as massless particles, yet experimental evidence from neutrino oscillation data suggests otherwise, indicating they possess tiny but non-zero masses. This revelation solidifies the presence of neutrino mixing, implying that at least two neutrinos have non-zero masses [1–3]. Unlike other fermions in the SM, neutrinos lack right-handed counterparts, precluding them from acquiring masses through the Higgs mechanism. However, the introduction of a dimension-five Weinberg operator [4–6] offers a plausible mechanism for neutrino

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A new Wolfenstein-like expansion of lepton flavor mixing towards understanding its fine structure

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Abstract

Taking the tri-bimaximal flavor mixing pattern as a particular basis, we propose a new way to expand the 3×3 unitary Pontecorvo-Maki-Nakagawa-Sakata (PMNS) lepton flavor mixing matrix U in powers of the magnitude of its smallest element $\xi \equiv |U_{e3}| \simeq 0.149$. Such a Wolfenstein-like parametrization of U allows us to easily describe the salient features and fine structures of flavor mixing and CP violation, both in vacuum and in matter.

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The non-first-order-factorizable contributions to the three-loop single-mass operator matrix elements $A_{Qg}^{(3)}$ and $\Delta A_{Qg}^{(3)}$

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Abstract

The non-first-order-factorizable contributions[1] to the unpolarized and polarized massive operator matrix elements to three-loop order, $A_{Qg}^{(3)}$ and $\Delta A_{Qg}^{(3)}$, are calculated in the single-mass case. For the ${}_2F_1$-related master integrals of the problem, we use a semi-analytic method based on series expansions and utilize the first-order differential equations for the master integrals which does not need a special basis of the master integrals. Due to the singularity structure of this basis a part of the integrals has to be computed to $O(\varepsilon^5)$ in the dimensional parameter. The solutions have to be matched at a series of thresholds and pseudo-thresholds in the region of the Bjorken variable $x \in]0, \infty[$ using highly precise series expansions to obtain the imaginary part of the physical amplitude for $x \in]0, 1]$ at a high relative accuracy. We compare the present results both with previous analytic results, the results for fixed Mellin moments, and a prediction in the small-x region. We also derive expansions in the region of small and large values of x. With this paper, all three-loop single-mass unpolarized and polarized operator matrix elements are calculated.

[1]The terms 'first-order-factorizable contributions' and 'non-first-order-factorizable contributions' have been introduced and discussed in Refs. [1,2]. They describe the factorization behaviour of the difference- or differential equations for a subset of master integrals of a given problem.

Testing the presence of QGP in small systems using (multi-)strange hadron correlations with a ϕ meson

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Abstract

The study delves into the enhanced production of strange and multi-strange hadrons in proton-proton collisions at LHC. Novel observables are proposed to distinguish between models describing existing data with or without the assumption of a QGP. Two models are explored: Epos4, based on core-corona separation between a QGP phase and a vacuum phase, and Pythia 8.3, based on microscopic interactions between Lund strings. The observables are based on an event selection requiring the presence of a ϕ-meson. Correlations between the ϕ and (multi-)strange hadrons are shown to be an excellent discriminator between the two types of models. These observations emphasize the need for further testing in upcoming LHC Runs, leveraging improved detectors and increased data collection.

Charge-conjugation asymmetry and molecular content: the $D_{s0}^*(2317)^\pm$ in matter

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We analyze the modifications that a dense nuclear medium induces in the $D_{s0}^*(2317)^\pm$ and $D_{s1}(2460)^\pm$. In the vacuum, we consider them as isoscalar $D^{(*)}K$ and $\overline{D}^{(*)}\overline{K}$ S-wave bound states, which are dynamically generated from effective interactions that lead to different Weinberg compositeness scenarios. Matter effects are incorporated through the two-meson loop functions, taking into account the self energies that the $D^{(*)}$, $\overline{D}^{(*)}$, K, and $\overline{K}$ develop when embedded in a nuclear medium. Although particle-antiparticle $[D_{s0,s1}^{(*)}(2317,2460)^+$ *versus* $D_{s0,s1}^{(*)}(2317,2460)^-]$ lineshapes are the same in vacuum, we find extremely different density patterns in matter. This charge-conjugation asymmetry mainly stems from the very different kaon and antikaon interaction with the nucleons of the dense medium. We show that the in-medium lineshapes found for these resonances strongly depend on their $D^{(*)}K/\overline{D}^{(*)}\overline{K}$ molecular content, and discuss how this novel feature can be used to better determine/constrain the inner structure of these exotic states.

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I. INTRODUCTION

The $D_{s0}^*(2317)^\pm$ state was first reported by the BaBar Collaboration in 2003 [1], and was a little after confirmed by CLEO in a Ref. [2] where the observation of the $D_{s1}(2460)^\pm$ was also claimed. These resonances lie far below the predictions for the two expected broad P-wave $c\bar{s}$ mesons [3–9], while they are located near the DK and D^*K thresholds, respectively, at about 45 MeV below them. Both states are isoscalars [$I(J^P) = 0(0^+)$ and $I(J^P) = 0(1^+)$, respectively] and thus strong isospin-violating decays are possible only to the isovector channels $D_s^{(*)}\pi$ leading to very small widths ($\lesssim 4$ MeV at 95% confidence level [10]).

The $D_{s0}^*(2317)$ and $D_{s1}(2460)$ states were, together with the $\chi_{c1}(3872)$, some of the first ever exotic hadronic states discovered. More specifically, the $D_{s0}^*(2317)$ and $D_{s1}(2460)$ are exotic in the sense that they give rise to three puzzles [11],

1. The masses for both states are significantly lower than the predictions stemming from the Godfrey and Isgur quark model [3], which was incredibly successful at the time (and even now).
2. The splitting between the D_{s1} and the D_{s0}^* is equal (up to a few MeV) to the mass difference between the D^* and D mesons.
3. The mass of the $D_0^*(2300)$ state, which does not contain any strange quark, is found to be larger than that of the $D_{s0}^*(2317)$, even though one should expect $c\bar{s}$ states to be in general heavier than $c\bar{\ell}$ ($\ell = u, d$) ones (hierarchy puzzle).

These problems are naturally solved within the chiral molecular picture, with a double pole structure for the broad $D_0^*(2300)$ resonance, and large (dominant) DK and D^*K components [12, 13] in the $D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$ cases, respectively. In this scheme [11, 14], the SU(3) $D_{(s)}^{(*)}\phi$ (with ϕ a Goldstone boson) S-wave scattering, in the $J^P = 0^+$ and 1^+ sectors, is studied using next-to-leading (NLO) heavy meson chiral perturbation theory[1] (HMChPT)

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[1] An effective Lagrangian that describes the low momentum interactions of mesons containing a heavy quark with the pseudo-Goldstone bosons π, K and η. It is invariant under both heavy quark spin and chiral $\mathrm{SU}(3)_L \times \mathrm{SU}(3)_R$ symmetries [15, 16].

Dual symmetries of dense three and two-color QCD and some QCD-like NJL models

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In this paper the symmetry properties of the phase diagram of dense quark matter composed of u and d quarks with two or three colors has been investigated in the framework of massless (3+1)-dimensional Nambu–Jona-Lasinio (NJL) and QCD models. It turns out that in the presence of baryon μ_B, isospin μ_I, chiral μ_5 and chiral isospin μ_{I5} chemical potentials the Lagrangians of these models are invariant under the so-called dual transformations. Consequently, the entire NJL model (or QCD) thermodynamic potentials are dually symmetric. In particular, it means that in the total $(\mu_B, \mu_I, \mu_5, \mu_{I5})$-phase portraits of these models the chiral symmetry breaking (CSB) and charged pion condensation (PC) phases are arranged dually conjugated (or symmetrical) to each other (in the case of three-color models). Whereas in the case of two-color quark matter, these models predict the entire phase structure in which there are dual symmetries between CSB, charged PC and baryon superfluid phases.

I. INTRODUCTION

Earlier, it was established on the basis of some (1+1)- and (2+1)-dimensional massless quantum field theory models with four-fermion interactions (and extended by quark number μ and chiral μ_5 chemical potentials) that in (toy) dense baryonic matter described in the framework of these low-dimensional models there is a duality correspondence $\mathcal{D}$ between the chiral symmetry breaking (CSB) and superconductivity phenomena [1–4]. As it turned out (see, e.g., in Refs. [2, 4]), this dual correspondence (or symmetry) $\mathcal{D}$ is based on the invariance of the model Lagrangian with respect (i) to the so-called Pauli-Gursey (PG) transformations of spinor fields $\psi(x)$ [5, 6], and (ii) simultaneously performed permutations of the values of the coupling constants in the CSB and superconducting channels, as well as values of chemical potentials, $\mu \leftrightarrow \mu_5$. Under the PG transformation the Lagrangian term $(\overline{\psi}\psi)^2$ responsible for the quark-antiquark interaction channel is transformed into the corresponding Lagrangian term $(\psi\psi)^2$ describing the quark dynamics in the superconducting interaction channel, and vice versa. Moreover, the Lagrangian terms $\overline{\psi}\gamma^0\psi$ and $\overline{\psi}\gamma^0\gamma^5\psi$ (which are the quark number and chiral densities, respectively), corresponding to the chemical potentials μ and μ_5 of the model are also transformed into each other. Due to this fact, the dual invariance $\mathcal{D}$ of the Lagrangian leads to the full (μ, μ_5)-phase diagram of dense quark matter, in which CSB and superconducting phases are dually conjugated to each other. It means that they are located mirror-symmetrical with respect to the $\mu = \mu_5$ line of the phase diagram. In addition, many characteristics of dense medium, calculated in one of the phases, are easily extrapolated to the dually conjugated phase of matter. So, the dual symmetry $\mathcal{D}$ of the model significantly simplifies the investigations of its thermodynamic properties.

Then, the possibility for duality correspondence between other physical phenomena has been investigated in the framework of the massless two-flavor (3+1)-dimensional Nambu–Jona-Lasinio (NJL) model [7] composed of N_c-colored u and d quarks. This simplest NJL model describes phenomena associated only with quark-antiquark interaction channels. In addition, the Lagrangian of the model was extended by the baryon μ_B, isospin μ_I and chiral isospin μ_{I5} chemical potentials, and its thermodynamic potential (TDP) was calculated in the leading order of the large-N_c expansion (or in the mean-field approximation), which describes the phase structure of dense quark matter with nonzero baryon, isospin and chiral isospin densities. As it was shown in Ref. [7], in this approximation the TDP possesses the symmetry with respect to the rearrangement of the order parameters of the CSB and the charged pion condensation (PC) phases, as well as the simultaneous transformation of $\mu_I \leftrightarrow \mu_{I5}$. Due to this symmetry of the TDP, which we call the dual symmetry between CSB and charged PC phases, it turns out that at each fixed μ_B the CSB and charged PC phases are arranged mirror-symmetrically relative to the line $\mu_I = \mu_{I5}$ on the corresponding (μ_I, μ_{I5})-phase diagram of the model. It means that knowing the phase (and its properties) of the model at, e.g., $\mu_I < \mu_{I5}$, it is possible to find what a phase (as well as its properties) is realized at $\mu_I > \mu_{I5}$. Hence, in the mean-field approximation in the above-mentioned simplest NJL model there is a duality between CSB and charged PC phenomena. It is a consequence of the corresponding dual symmetry of the (mean-field) TDP of the NJL model. (We emphasize in particular that in the proposed paper, the dual properties of only some (3+1)-dimensional models are considered. However, we note that various aspects of the duality between CSB and charged PC phenomena were also considered in some (1+1)-dimensional toy models with four-fermion interactions [8, 9].) Then it was shown in Ref. [10] that an additional chiral chemical potential μ_5 does not spoil this duality. However, it must be borne in mind that the duality between CSB and charged PC is exact (in the large-N_c or mean-field approximations) only in the chiral limit, i.e. when the bare quark mass m_0 is zero. At $m_0 \neq 0$ the duality between CSB and charged PC is only approximative [11].

A Phenomenological Study of WIMP Models

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Pole properties of a resonance: When to subtract partial-decay widths to obtain the pole widths*

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When a resonance lies near the threshold of a heavier channel, an interesting feature can occur. The paradigmatic example employed here is the scalar isoscalar $f_0(980)$ resonance that couples to the lighter $\pi\pi$ and heavier $K\bar{K}$ channels. It is shown that the decay width is given by the sum or subtraction of the partial decay widths depending on whether the pole lies in the Riemann sheet that is contiguous with the physical one above or below the $K\bar{K}$ threshold, respectively. Next, we show that the usually disregarded renormalization of bare parameters in Flatté or energy-dependent Breit-Wigner parameterizations is essential to extract physical information. The compositeness of the $f_0(980)$ by using a Flatté parameterization matched to reproduce the pole properties obtained from Roy equations and other analytic constraints is evaluated.

1. Introduction

A Flatté parameterization [1] is typically used for describing a resonance that lies near a heavier threshold. Let us denote by $i = 1$ and 2 the light and heavy channels, respectively. To fix ideas think of the $f_0(980)$ and the scalar isoscalar channels $\pi\pi$ and $K\bar{K}$, in this order. Then, around the $K\bar{K}$ threshold an S-wave amplitude is written as

$$t_{ij} = \frac{\tilde{g}_i \tilde{g}_j}{E - E_f + i\frac{\widetilde{\Gamma}_1}{2} + \frac{i}{2}\tilde{g}_2^2\sqrt{m_2 E}} \,, \tag{1}$$

with E the total energy measured with respect to the two-kaon threshold. The kinematics for the $K\bar{K}$ channel is treated nonrelativistically. This parameterization is determined by three *bare* parameters: The bare coupling $\tilde{g}_2$, the bare width $\widetilde{\Gamma}_1$ and the bare resonance mass E_f. $\widetilde{\Gamma}_1$ is related to the

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Collective excitations and low-energy ionization signatures of relativistic particles in silicon detectors

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Abstract: Solid-state detectors with a low energy threshold have several applications, including in direct-detection searches of non-relativistic halo dark-matter particles with sub-GeV masses. Moreover, when searching for relativistic or quasi-relativistic beyond-the-Standard-Model particles (i.e., $v/c \gtrsim 0.01$) that have an enhanced cross section for small energy transfers, a comparatively small detector with a low energy threshold may have better sensitivity than a larger detector with a higher energy threshold. In this paper, we provide accurate calculations of the low-energy ionization spectrum from high-velocity particles scattering in a dielectric material. We focus on silicon, although our results can be easily applied to other materials. We consider the full material response, in particular also the excitation of bulk plasmons. We generalize the energy-loss function to relativistic kinematics, and benchmark existing tools used for halo dark-matter scattering against publicly available electron energy-loss spectroscopy data. Compared to calculations of energy loss that are commonly used in the literature, such as the Photo-Absorption-Ionization model or the free-electron model, the inclusion of collective effects shifts the recoil ionization spectrum towards higher energies, typically peaking around 4–6 electron-hole pairs. We apply our results to the three benchmark examples: millicharged particles produced in a beam, neutrinos with a magnetic dipole moment produced in a reactor, and dark-matter particles that are upscattered by cosmic rays or in the Sun. Our results show that the proper inclusion of collective effects typically enhances a detector's sensitivity to these particles, since detector backgrounds, such as dark counts, peak at lower energies.