The complex structure of strong interactions in Euclidean and Minkowski space

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ECT*

Book of Abstracts

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Mesons, baryons and the confinement/deconfinement transition.

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Lattice simulations have clearly established that the low- and high-temperature regimes of QCD are controlled by distinct active degrees of freedom, hadrons on the one side, and quarks and gluons on the other side. Yet, many continuum studies of the confinement/deconfinement transition rely on the Polyakov loop which measures how energetically costly it is to bring an external quark probe into a bath of quarks and gluons. In the low temperature phase, this energy cost is very large which one interprets as the system being confined. Yet this energy cost is finite which seems to indicate that bringing a quark probe remains possible, in blatant tension with the change in degrees of freedom referred to above. We resolve this tension by studying the net quark number of the bath as one brings an external quark probe into the medium. We show that, while in the deconfined phase, the net quark number gained by the system is equal to the quark number of the probe, in line with the idea that, in this phase, one can bring a quark without significantly affecting the bath, in the confined phase, the net quark number gained by the system is equal to 0 or 3 (depending on the chemical potential), which we interpret as the medium forming either mesons or baryons to screen the quark probe.

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The infrared safe Minkowskian Curci-Ferrari model

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We discuss the existence of Landau-pole-free renormalization group trajectories in the Minkowskian version of the Curci-Ferrari model and study how those are connected to the trajectories of the Euclidean version of the model.

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Center-symmetric Landau gauge on the lattice: symmetry constraints and the gluon propagator

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We discuss a lattice implementation of the center-symmetric Landau gauge, and we show results for constraints in the link average and in the gluon propagator.

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Hadronic Structure and Contour Deformations

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The internal structure of hadrons can be described in terms of structure functions that encode, for example, the momentum and spin distributions of their constituents. Parton distribution functions (PDFs) and Transverse Momentum Distributions (TMDs), for example, describe the quark and gluon momentum distributions inside a hadron. These distribution functions are, however, not easy to calculate, because they are defined on the light front, whereas most hadron calculations are performed in a Euclidean metric. We are developing a new method to compute the parton distributions (TMDs and PDFs) from hadronic matrix elements using contour deformations. We will illustrate the method for a simple system of two interacting scalar particles of equal mass, using an handbag approximation to the matrix element, that includes the two-body Bethe-Salpeter amplitude as input (calculated from its Bethe-Salpeter Equation).

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Distribution Functions Using Continuum Schwinger Function Methods

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Understanding the internal structure of hadrons is a fundamental challenge in nonperturbative QCD, where the emergent phenomena of confinement and dynamical chiral symmetry breaking play central roles. In this talk, I present recent progress in the study of hadronic distribution functions using continuum Schwinger function methods formulated in Euclidean space. Focusing on the parton distribution functions (DFs) of the pion, kaon, radially excited pion, and the nucleon, I will discuss how key features of QCD dynamics are encoded in these observables. The talk will also highlight results for the pion Boer-Mulders function, providing insight into spin-momentum correlations and the transverse structure of the pion. Furthermore, I will present studies of the pion and kaon generalized parton distributions (GPDs), which offer a multidimensional view of hadronic structure. These continuum approaches yield results that complement lattice QCD and provide valuable benchmarks for ongoing and future experimental investigations into the rich structure of strongly interacting matter.

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Unveiling the Strong Interaction origin of Baryon Masses with Lattice QCD

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Here we present first-principles lattice QCD calculations using comprehensive gauge ensembles that accurately predict ground state spin-1/2 and spin-3/2 baryon masses with light, strange, and charm quarks within 1\% of experimental values. At the \(\overline{\mathrm{MS}}\) 2 GeV scale, our results unveil two fundamental mass generation mechanisms for those baryon masses in QCD: 1) the flavor-dependent enhancement of Higgs contributions, 4-8 for light, 2-3 for strange, and 1.2-1.3 for charm quarks; and 2) the flavor-insensitive contribution 0.8-1.2 GeV from gluon quantum anomaly.

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Excited charm/charmonium mesons and exotics from lattice QCD

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I will summarise some recent progress in studying hadrons using lattice QCD. The spectroscopy and interactions of hadrons probe the strongly-interacting regime of QCD, and in recent years experiments have observed a number of puzzling hadrons that challenge our understanding of the strong interaction. Lattice QCD provides a method for performing first-principles computations of the properties of hadrons and hence a QCD-based understanding of the phenomena. However, the majority of hadrons decay strongly, i.e. they are resonances, and lattice calculations of these are challenging. I will present a selection of work that has advanced our understanding of hadrons such as results relevant for the exotic doubly-charmed $T_{cc}(3875)$ observed by LHCb, scalar and tensor charmonium resonances, and the $D_0^*(2300)$ and enigmatic $D_{s0}^*(2317)$ charm mesons.

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Goldstone bosons at finite temperature

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Temperature has a significant effect on the properties of QFTs with spontaneously broken symmetries, in particular for the massless Goldstone bosons that exist in the vacuum state. In this talk I will discuss recent results which indicate that Goldstone modes persist at high temperatures, even if the symmetry is restored, and that they have the properties of screened massless excitations, so-called thermoparticles. This has important implications for the phase structure of QFTs at finite temperature.

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Extracting Phenomenology from Dyson-Schwinger equations: The $^3P_0$ Model and (Hybrid) Meson Decays

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Dyson–Schwinger equations (DSEs) provide a non-perturbative framework for computing QCD Green's functions. When constrained by lattice QCD data, these solutions—originally formulated in Euclidean space—can potentially be analytically continued to Minkowski space. Achieving this continuation enables the extraction of hadronic phenomenology directly from non-perturbative DSE calculations.

Meson decay models frequently invoke the creation of quark–antiquark pairs in a $^3P_0$ state —a scalar configuration that does not arise in perturbative QCD due to chiral symmetry. By employing DSEs constrained by lattice data for the quark propagator and quark–gluon vertex—naively extended into the Minkowski domain—we explore (in https://arxiv.org/abs/2312.14994) how such a scalar vertex may emerge dynamically in tandem with constituent quark mass generation.

Additionally, several established techniques will be discussed for reliably extending Euclidean DSE solutions to Minkowski space. These methods provide a foundation for extracting further phenomenological insights, particularly in the context of hybrid meson decays involving quark–antiquark–gluon (qqg) states, within a fully non-perturbative QCD framework.

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The Bell-CHSH inequality in 2D fermion theories: numerical and formal study via bumpified Haar wavelets, from free to interacting case

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We investigate the violation of the Bell-CHSH inequality in the vacuum state in the context of Quantum Field Theory. Summers and Werner showed in the eighties, using tools from algebraic quantum field theory and operator analysis, that test functions exist that lead to an asymptotic reaching of Tsirelson's upper bound violation of 2 \sqrt 2.

We propose a different strategy that allows to explicitly construct such test functions. We apply the method to massless spinor fields in (1+1)-dimensional Minkowski space-time. Alice's and Bob's test functions are numerically constructed, first by employing Haar wavelets which are then massaged into proper C^\infty bump functions via a smoothening procedure relying on the Planck-taper window function. Relativistic causality is implemented by requiring the support of Alice's and Bob's test functions to be located in the left and right Rindler wedges, respectively. Violations of the Bell-CHSH inequality as close as numerically desired to Tsirelson's bound of 2 \sqrt 2 are reported.

The bumpification procedure can be brought under rigorous mathematical control. For the asymptotic reaching of the Tsirelson's bound, we show how to match the issue onto a Toeplitz matrix

problem and its spectral properties. This allows to already give a formal proof for reaching 99,3% of the upper bound.

We end by commenting on the extra portal, compared to earlier works, that our numerical procedure opens to scrutinize Bell-CHSH inequalities with generic, interacting Quantum Field Theories, a yet unexplored area of research. Here, the spectral representation in Minkowski space enters the game.

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Semiclassics for QCD vacuum structure via T^2 compactification

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We explore the QCD vacuum structure, using a novel semiclassical method on $\mathbb{R}^2\times T^2$ with 't Hooft and baryon magnetic fluxes. In this setup, it is conjectured that no phase transition occurs when the size of T^2 is varied (adiabatic continuity). If this holds true, the analysis at small T^2 can predict qualitative features of the QCD vacuum structure on $\mathbb{R}^4$.
At small T^2, through semiclassical analysis, we derive a 2D effective theory, where the confining vacuum is described as a dilute gas of center vortices. This 2D effective theory yields a plausible θ-dependence of the QCD vacuum. Moreover, the resulting 2D effective theory is analogous to the chiral Lagrangian with a periodicity-extended η' meson. This periodicity extension arises from incorporating the gluonic multi-branch structure into the η' degrees of freedom, and it improves the consistency of global aspects of the chiral Lagrangian.

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Exploring three-point functions in the complex plane

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In the calculation of bound state properties, models for interactions play a crucial role in identifying underlying mechanisms and also in obtaining quantitative results. Their construction is typically not only guided by symmetries but also by the complexity one can computationally handle when using them in bound state and related equations. In this context, one advantage of models is that their analytic structure is known. When, on the other hand, the corresponding elementary correlation functions are calculated from their own equations, their analytic structure is more difficult to assess with limited possibilities to influence it. In this talk, I will illustrate the obstacles of this approach for three-point functions of Yang-Mills theory which are essential ingredients in the calculation of glueballs.

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The setting sun diagram with complex external momenta

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The issue of analytically continuing Feynman integrals from Euclidean to Minkowski signature is revisited with complex momenta,which become relevant in theories where complex poles are observed. Although this continuation is well-known in terms of the Källén-Lehmann representation, some potential alternative takes, which are equivalent for real momenta, will lead to different results for complex momenta. We present our analysis for the simple case of the setting sun diagram in d=2.

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Testing infrared confining models beyond fundamental correlation functions

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Infrared-confining models such as the Curci-Ferrari and Refined Gribov-Zwanziger frameworks are known to provide modified gluon propagators that incorporate nonperturbative mass scales and/or complex analytic structures, while also yielding results compatible with benchmark nonperturbative approaches such as Lattice QCD. These models are largely evaluated through gluon, ghost and quark correlation functions, so that their predictive power for physical observables remains to be better explored. In this talk, I discuss how one can assess the efficacy of infrared-confining models in two distinct phenomenological contexts: the proton and neutron anomalous magnetic moments and color superconductivity in cold, dense matter. In particular, we analyze one-loop corrections to the quark-photon vertex and extract the F2 form factor for the different confining models. The associated proton and neutron magnetic moments are constructed using the constituent quark model to show how confining parameters impact predictions. Finally, in the superconducting context, we investigate how confining propagators impact the frequency-dependent gap structure in a Yukawa-type model. Overall, our results indicate that infrared-confining models provide consistent predictions for distinct QCD observables, while yielding quantitative discrepancies that might allow to discriminate between them.

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Constructing Local Gauge-Invariant Operators: The Higgs Model as a Case Study

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In gauge field theory, we follow the fundamental principle that physical observables must be gauge independent. The most straightforward way to ensure this is to work with gauge-invariant operators, since their correlation functions are expected to be gauge independent. In addition to this

crucial property, in theories where the physical subspace has a semi-positive norm, correlation functions of gauge-invariant operators exhibit consistent spectral properties, as will be discussed in my talk.

The Higgs model is the most prominent example of a theory with a perturbatively semi-positive normed physical space. As such, it provides a particularly valuable laboratory for investigating key questions that go beyond the perturbative regime, such as confinement—especially given that lattice results suggest the existence of confining phases.

In my talk, I will also present a general framework for constructing gauge-invariant dressed fields in different gauges and discuss how this framework can be implemented at the quantum level.

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Parton fragmentation functions as a timelike extension of distribution functions

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Fragmentation functions describe the number of hadrons inside a given parton in the light-front momentum-fraction range [z,z+dz]. They are ubiquitous, appearing in most of the factorisation formulae used to relate some given process to a structural hadron property. However, practically nothing is known about them. Results obtained via phenomenological fits are practitioner dependent and in mutual disagreement. No algorithm exists today for their computation via lattice-regularized QCD, in large part because FFs are the timelike twins of distribution functions. Nevertheless, dependable, realistic results must become available before data from modern and anticipated facilities can properly be understood as representative of strong interaction physics. This presentation will describe one practicable approach to the parameter-free prediction of FFs using continuum Schwinger function methods.

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Emergent Hadron Mass and Pion/Kaon/Nucleon Form Factors

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After reviewing the Emergeht Hadrom Mass (EHM) framework I will discuss recent results onf the pion, kaon and nucleon electromagentic and gravitational form factors.

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Functional renormalization of QCD in 1 + 1 dimensions: Four-fermion interactions from quark-gluon dynamics

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Quantum chromodynamics in two spacetime dimensions is investigated with the Functional Renormalization Group. We use a functional formulation with covariant gauge fixing and derive Renormalization Group flow equations for the gauge coupling, quark mass and an algebraically complete set of local fermion-fermion interaction vertices. The flow, based on a convenient Callan–Symanzik-type regularization, shows the expected behavior for a super-renormalizable theory in the ultraviolet regime and leads to a strongly coupled regime in the infrared. Through a detailed discussion of symmetry implications, and variations in the gauge group and flavor numbers, the analysis sets the stage for a more detailed investigation of the bound state spectrum in future work.

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Multiquark states with functional methods

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I will discuss recent applications of functional methods, in particular the combination of Dyson-Schwinger and Bethe-Salpeter equations, to hadron spectroscopy. There are various ongoing efforts in investigating the properties of exotic hadrons and multiquark states such as tetraquarks, pentaquarks and hexaquarks. In this talk I will focus on four-quark states in the heavy-light sector and briefly mention applications to higher multiquark states.

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New Methods in Numerical Analytic Continuation

Author: William Jay[1]

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Problems of analytic continuation arise frequently in particle physics, especially in the context of lattice field theory calculations carried out in Euclidean time. This talk will describe recently developed methods for carrying out this procedure numerically, discussing the connection to scattering observables.

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The full QCD gluon and ghost propagators and the transition to the deconfinement regime

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The gluon and ghost propagators are computed in full QCD using non-perturbative order-a improved Clover fermions above and below the deconfinement temperature. Our simulations employ a setup that yields a pion mass of 290MeV at T=0. Defining a gluon mass m_g from the inverse of the gluon propagator *at zero momenta, we show that both the electric and magnetic masses have a smooth behaviour with T and above T_c. In particular,* they are compatible with the predictions of thermal perturbation theory based on the hard thermal loop expansion.

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Radiative corrections in the Refined Gribov-Zwanziger framework and its coupling to matter

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The Refined Gribov-Zwanziger (RGZ) scenario is one of the most well-developed frameworks to account for the existence of (infinitesimal) Gribov copies and further non-perturbative effects such as the formation of condensates. Most progress has been achieved in the Landau gauge. The theory features a tree-level gluon propagator that reaches a non-vanishing value at zero momentum and a non-enhanced ghost propagator in the deep infrared. One of the key questions is if such a structure is stable against quantum corrections. Another issue to be faced is how to couple matter in this context and if the underlying RGZ-matter system provides a good description of matter correlation functions (in the presence of radiative corrections). Finally, a long-standing issue is the fate of BRST symmetry in such a theory and how to extend it to different gauges. In this talk, I will report on recent developments on the aforementioned issues and discuss future research directions to be taken in order to strengthen or invalidate the RGZ(-matter) scenario as an efficient description of the infrared regime of Yang-Mills theories/QCD. Main challenges and difficulties will also be discussed.

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The gluon propagator at finite temperature and density

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During this talk we will present recent results on the Landau-gauge infrared gluon propagator in Euclidean space at finite temperatures and baryonic densities, as computed within the framework of the screened massive expansion of QCD by making use of a simple model for the infrared quark masses. We will discuss the behavior of the propagator and its sensitivity on the deconfinement phase transition and on the parameters of the expansion. At the end of the talk we will also provide some insight into ongoing research concerning the analytic structure of the propagator.

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Distribution Functions of a Radially Excited Pion

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A nonperturbatively-improved, symmetry-\linebreak preserving approximation to the quantum field equations relevant in calculations of meson masses and interactions is used to deliver predictions for all distribution functions (DFs) of the ground state pion, π_0, and its first radial excitation, π_1, \emph{viz}.\ valence, glue, and sea. Regarding Mellin moments of the valence DFs, the $m = 0, 1$ moments in both states are identical; but for each $m \geq 2$, that in the π_0 is greater than its partner in the π_1. Working with such information, pointwise reconstructions of the hadron-scale $\pi_{0,1}$ valence DFs are developed. The predicted π_0 valence DF is consistent with extant results. The π_1 valence DF is novel: it possesses three-peaks, with the central maximum partnered by secondary peaks on either side, each separated from the centre by a zero: the zeroes lie at $x \approx 0.2, 0.8$ and the secondary peaks at $x \approx 0.1, 0.9$. Evolution to $\zeta = 3.2\,\text{GeV}$, a typical scale for nonperturbative calculations, is accomplished using an evolution scheme for parton DFs that is all-orders exact. At this higher scale, differences between the $\pi_{0,1}$ valence DFs remain significant, but analogous differences between glue and sea DFs are far smaller. This analysis shows that, owing to constraints imposed by chiral symmetry and the pattern by which it is broken in Nature, there are noticeable differences between the structural properties of the pion ground state and its radial excitations.

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S-matrix approach to the Thermodynamics of Hadrons

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I will present how the S-matrix formalism enables a model-independent description of hadronic matter by linking scattering phase shifts to an effective density of states. This approach naturally incorporates broad resonances and repulsive interactions, offering a robust framework for thermal QCD.

Applied to the LHC proton yield anomaly, it helps resolve the "proton puzzle"by capturing essential features of the baryon spectrum, with direct implications for lattice QCD observables like baryon-charge correlations.

I will also highlight new insights into in-medium effects, particularly three-body forces in the $S = -2, -3$ sector, and their role in shaping QCD susceptibilities.

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Center vortices and gluon mass generation

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I will show results of a study* using continuum methods establishing a connection between center vortices and gluon mass generation in 3+ 1 dimensions Yang-Mills theory. I will show that such

a connection can be established within the Hamiltonian framework by employing a vacuum wave-functional peaked on center vortices —a framework originally introduced to explain the Wilson loop area law. We derive an analytical expression for the chromomagnetic field correlation function revealing an infrared mass scale.

*D.R. Junior, GK, L.E. Oxman and B.R. Soares

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Kaon distribution functions from empirical information and all-orders evolutions

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Using available information from Drell-Yan data on pion and kaon structure functions, an approach is described which enables the development of pointwise profiles for all pion and kaon parton distribution functions without reference to theories of hadron structure. The key steps are construction of structure-function-constrained probability-weighted ensembles of valence DF replicas and use of an evolution scheme for parton DFs that is assumed to be all-orders exact.

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Gravitational form factors from Continuum Schwinger methods

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A unified set of predictions for nucleon gravitational form factors is obtained using continuum Schwinger methods (CSMs). A crucial aspect of the study is the self-consistent characterization of the dressed quark-graviton vertices, applied when probing each quark flavor inside mesons or nucleons. The calculations reveal that each hadron's mass radius is smaller than its charge radius, matching available empirical inferences.

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Welcome

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Introduction and overview

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Finite Volume Thermodynamics in a Magnetic Field

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Polyakov Loop and Center Symmetry: Interpretations in Euclidean and Minkowski Space

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Closing

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Breaking through the complexity of QCD in the Minkowski space-time

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This contribution concerns the complexity of the Hamiltonian formulation of QCD in the Minkowski space-time. The talk will include suggestions for overcoming the issues using the front form of dynamics and eigenvalue equations for describing bound states of the quanta of quark and gluon fields, and a method for computing effective Hamiltonians in quantum field theory, called the renormalization group procedure for effective particles. The latter is meant to provide a mathematical relationship between the complex parton-model picture of hadrons, viewed as relativistic many-body systems, with their simple classification as mostly made of just two or three constituent quarks. An outline of the steps of the computational scheme for deriving the quark and gluon structure of hadrons is provided as a summary. For references, see K. Serafin, M. Gomez-Rocha, J. More, S.D. Glazek, Dynamics of heavy quarks in the Fock space, Phys. Rev. D, 109, 016017 (2024).