Hamiltonian Field Theory for QCD and Hadron Physics

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Book of Abstracts

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Multi-scale Hamiltonian Formulations of Quantum Field Theories

Author: Wayne Polyzou[1]

[1] *University of Iowa*

Corresponding Author: polyzou@uiowa.edu

I will discuss formally exact Hamiltonian representations of quantum field theories based on Daubechies wavelets. Daubechies wavelets are an orthonormal basis of compactly supported functions on the real line. They are generated from the fixed point of a renormalization group equation by translations and dyadic scale transformations.
There are an infinite number of basis functions with support in any open set. Using this basis local fields can be expressed as infinite linear combinations well-defined local observables. In this representation ill-defined local products of fields are replaced by infinite linear combinations of products of well-defined operators.
This can be applied to express all ten Poincaré generators as infinite linear combinations of products of well defined operators. The wavelet representation of the theory has natural volume and resolution cutoffs, and the dynamical operators at different resolution are self-similar, where the coefficients of operators different scales can be computed exactly using renormalization group methods. The method can be applied to both canonical or light front formulations of quantum field theory. I will discuss their potential use in real-time path integrals and some speculations on how to apply multi-scale methods to construct irreducible algebras of locally gauge invariant observables for use in gauge theories.

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Small-x divergences in the front form Hamiltonian formulation of QCD

Author: Stanislaw Głazek[1]

[1] *University of Warsaw*

Corresponding Author: stanislaw.glazek@fuw.edu.pl

Wilson et al. proposed in Phys. Rev. D 49, 6720, (1994) to deal with the QCD front form Hamiltonian divergences due to gluons with small hadron momentum fraction x, such as in the instantaneous gluon exchange between quarks, by introducing tree level counter terms. These small-x divergences and counter terms significantly complicate access to the logarithmically scale-dependent dynamics of hadronic constituents. An alternative approach will be discussed. The transverse gluons are given an arbitrarily small mass and a scalar octet field is introduced to stand for the longitudinal gluons. The scalar field couples to the quark and gluon color currents proportionally to the gluon mass so that the coupling vanishes in the limit of the mass going to zero. Ultraviolet and small-x divergences are treated in a common way using a correspondingly adjusted regularization and renormalization group procedure. There is no need for the tree-level counter terms proposed by Wilson et al. The Hamiltonian approach is thus simplified. The limit of the resulting renormalized, logarithmically scale-dependent theory when the gluon mass parameter is going to zero appears worth studying for application in phenomenology of hadrons made of quarks and gluons that are asymptotically free at short and confined at long distances.

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Electron and Photon Gravitational form factors in light-front Hamiltonian QED

Author: Jai More[1]

[1] *Indian Institute of technology, Bombay*

Corresponding Author: more.physics@gmail.com

In the present work, we have investigated the gravitational form factors (GFFs) for an electron and photon in the light-front QED model. We consider a physical electron dressed consisting of a bare electron and a photon. The gravitational form factors are obtained in the form of the overlap of light-front wave functions. The GFF D is attributed to information like pressure, shear, and energy distributions. We also aim to obtain the results for the mechanical properties i.e. pressure and shear distribution for an electron and a photon and this work is ongoing.

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Hamiltonian light-front dynamics, holographic QCD and entanglement in high-energy scattering

Author: Guy F. de Teramond[1]

Co-authors: Hans Günter Dosch [2]; Stanley Brodsky [3]

[1] *Universidad de Costa Rica*

[2] *Heidelberg University*

[3] *SLAC National Accelerator Laboratory, Stanford University*

Corresponding Author: gdt@asterix.crnet.cr

The Hamiltonian formalism is a particularly useful framework to describe hadron bound states in QCD while generating the Hilbert space in terms of their constituents. The quantum entropy of any bound state is zero, but when the proton components are probed, for example by deep inelastic scattering, the study of the entropy of entanglement between the components and the rest of the proton leads to new insights on the high energy scattering behavior of hadrons. In this talk we examine how the growth above the classical geometric cross section is directly related to the increase of the internal quantum entropy from the entangled parton distribution in hadrons. We will also briefly examine the connection between the scale dependence of the Pomeron from the QCD evolution of the gluon distribution function, the rising of the integrated cross section in photoproduction of vector mesons, hadron multiplicity and entropy as recently discussed in [1].

[1] H. G. Dosch, G. F. de Téramond and S. J. Brodsky, "Entropy from entangled parton states and high-energy scattering behavior," [arXiv:2304.14207 [hep-ph]].

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Chiral spin symmetry of the confining Hamiltonian and its implications for hadrons and hot QCD.

Author: Leonid Glozman[1]

[1] *University of Graz*

Corresponding Author: leonid.glozman@uni-graz.at

We discuss the chiral spin symmetry of confinement in QCD and its implications for structure of hadrons as well as for hot QCD.

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Accelerating the timeline for quantum simulations in high energy physics

Author: Yingying Li[1]

[1] *University of Science and Technology of China (USTC)*

Corresponding Author: yingyingli1013@outlook.com

High energy physics is facing challenges of e.g., understanding the origin of observed baryon asymmetry, the nature of dark matter. Scenarios to address these challenges often involve dynamics that at present cannot be solved due to computational or theoretical limitations. An elegant solution exists in the form of real-time simulation, though hampered by limited quantum resources for the foreseeable future. In my talk, I will motivate the critical need for real-time simulation in high energy physics, discuss existing challenges and techniques involved. Then I will focus on improved Hamiltonians to lower the qubit requirements. With derivations of the matrix elements for the improved terms and constructions of the corresponding quantum circuits, we pave the way of simulating these improved Hamiltonians in real-time for general gauge theories.

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The effective potential of the Polyakov loop in the Hamiltonian approach to QCD

Authors: Hugo Reinhardt[1]; Markus Quandt[None]

[1] *Institute for Theoretical Physics, Tuebingen University*

Corresponding Author: h.reinhardt@uni-tuebingen.de

The effective potential of the Polyakov loop is investigated within the Hamiltonian approach to QCD in Coulomb gauge where finite temperature T is introduced by compactifying one space direction. We briefly review this approach and extend earlier work in the Yang-Mills sector by including dynamical quarks. In a first approximation, we follow the usual practice in functional approaches and include only one-loop contributions, with the finite temperature propagators replaced by their $T = 0$ counter parts. It is found that this gives a poor description of the phase transition, in particular for the case of full QCD with $N_f = 3$ light flavours. The physical reasons for this unexpected result are discussed, and pinned down to a relative weakness of gluon confinement compared to the deconfining tendency of the quarks. We attempt to overcome this issue by including the relevant gluon contributions from the two-loop terms to the energy. We find that the two-loop corrections have indeed a tendency to strengthen the gluon confinement and weaken the unphysical effects in the confining phase, while slightly increasing the (pseudo-)critical temperature T^* at the same time. To fully suppress artifacts in the confining phase, we must tune the parameters to rather large values, increasing the critical temperature to $T^* \approx 340\,\mathrm{MeV}$ for $G = SU(2)$.

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Quantum simulation of multi-particle jet evolution in a medium

Authors: Carlos Salgado[1]; Joao Barata[2]; Meijian Li[1]; Wenyang Qian[1]; Xiaojian Du[1]

[1] *University of Santiago de Compostela*

[2] *Brookhaven National Laboratory*

Corresponding Authors: carlos.salgado@usc.es, meijian.li@usc.es, jlourenco@bnl.gov, qian.wenyang@usc.es, xiaojian.du@usc.es

In recent years, a lot of effort has been put into expanding established jet-quenching formalisms to account for higher-order or energy-suppressed medium-induced effects. Understanding how such contributions emerge is important to have a more complete picture of jet evolution in the medium and to extract more detailed properties of the underlying matter. However, such efforts are in general plagued by technical difficulties related to the complexity of the calculations. In this talk, we show that quantum computers can be used as alternative theoretical labs to simulate jet evolution in the quark-gluon plasma. Based on the light-front Hamiltonian formalism, we construct a digital quantum circuit that tracks the evolution of a multi-particle jet probe within the $|q\rangle + |qg\rangle + |qgg\rangle$ Fock sectors in the presence of a stochastic color background, which is computationally expensive for classical simulation. Using the quantum simulation algorithm, we show that the jet evolution in the medium can be properly captured employing small lattices. Importantly, the simulations can be run in general stochastic backgrounds, surpassing many of the simplifying assumptions usually taken. We will show that the present strategy can be efficiently expanded to account for the production of multiple gluon radiations.

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QCD Hamiltonian without divergences

Author: Kamil Serafin[1]

[1] *Institute of Modern Physics, Chinese Academy of Sciences*

Corresponding Author: kserafin@fuw.edu.pl

I will present a plan for solving QCD. The first step requires calculating effective Hamiltonians using renormalization group procedure for effective particles (RGPEP). In the second step one diagonalizes the Hamiltonians using known methods (DLCQ, BLFQ, quantum computing, etc.). My confidence in the plan stems from the fact that both ultraviolet and small-x divergences are absent in the matrix elements of the effective Hamiltonians and because RGPEP plants the seed of confinement. The devil is in the details that will be discussed on the example of heavy quarkonium.

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Light Front Hamiltonian approach to bound states in QED and QCD

Author: James.P. Vary[1]

[1] *Iowa State University (ISU)*

Corresponding Author: jvary@iastate.edu

Light Front quantization of a Hamiltonian derived from quantum field theory has a long history. The introduction of Basis Light Front Quantization (BLFQ) has led to the development of Hamiltonians and numerical methods for solving both relativistic bound state and scattering applications in QED and QCD. For QCD applications in limited Fock spaces, one assumes a form of confinement based on light-front holography along with an additional longitudinal confinement. In applications limited to valence quarks, an effective one-gluon exchange interaction in light front gauge is employed. Recent applications include expanding Fock spaces beyond valence fermions to include the dynamical gauge degrees of freedom. Since the light front wave functions are interpreted as appropriate to a low-resolution scale, calculated observables such as parton distribution functions (PDFs) can be QCD-evolved to higher scales for comparison with experiments. I will survey recent applications to mesons and baryons and discuss prospects for future developments.

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Theoretical and algorithmic considerations for quantum computing non-Abelian lattice gauge theories

Author: Zohreh Davoudi[1]

[1] *University of Maryland, College Park*

Corresponding Author: davoudi@umd.edu

Quantum computing lattice gauge theories of relevance to nature requires a range of theoretical and algorithmic developments to make simulations amenable to near- and far-term computing. With a focus on the SU(2) lattice gauge theory with matter, I will motivate the need for efficient theoretical formulations, introduce general quantum algorithms that can simulate them efficiently, and discuss strategies for analyzing the required quantum resources accurately. These considerations will be of relevance to simulating other gauge theories of increasing complexity, including quantum chromodynamics.

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Lattice gauge theories: simulation strategies

Author: Enrique Rico Ortega[1]

[1] *UPV/EHU & Ikerbasque*

Corresponding Author: enrique.rico.ortega@gmail.com

We will discuss three different aspects in the simulation of lattice gauge theories:
(1) We will see how tensor network methods allow to have access to real-time dynamics in these systems.
(2) We will see how non-perturbative matrix elements (PDF, TMD,…), that are non local in both space and real-time and are essential to describe the scattering in particle physics, can be obtained from a quantum simulator.
(3) We will mention ways to prepare non-trivial many-body quantum states in gauge invariant models.

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The Price of Minkowski Lattice Gauge Theories

Author: Henry S. Lamm[1]

[1] *Fermilab*

Corresponding Author: hlamm@fnal.gov

Quantum computers open the possibility of efficiently simulating quantum field theories directly in Minkowski space through a Hamiltonian formulation. In order to take advantage of these new devices, a number of theoretical and algorithmic obstacles must be overcome. Resolving them in as resource effective way as possible could reduce the timescale for practical quantum advantage by decades. In this talk, we will discuss a number of problems and some solutions for simulating quantum field theories on quantum computers.

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Quantum Error Correction for Lattice Field Theories

Author: Alessandro Roggero[1]

[1] *University of Trento*

Corresponding Author: a.roggero@unitn.it

Quantum simulations on digital quantum devices have the promise of offering the possibility for non perturbative calculations of both static and dynamic properties of strongly coupled Lattice Field Theories. In order to deliver on this promise, large scale digital quantum calculations need to be protected using Quantum Error Correction (QEC). In this talk I will give a brief introduction to the main ideas behind QEC and how it is possible to design QEC protocols specifically suited for the simulation of gauge theories on the lattice.

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Studying the 3P0 decay model from QCD in Landau gauge

Authors: Reinhard Alkofer[1]; Felipe J. Llanes-Estrada[2]; Alexandre Salas-Bernárdez[2]

[1] *University of Graz*

[2] *Universidad Complutense de Madrid*

Corresponding Author: alexsala@ucm.es

Traditional lore of meson decays suggested that the production of a quark-antiquark pair from the chromoelectric field would happen in a 3P0 state (a scalar state with aligned spins and a relative L=1 wave). This are not the quantum numbers of the tree-level interaction in QCD. Moreover, they are not produced at any order in perturbation theory because the theory is to a good approximation chirally symmetric. Thus, such production vertex has to arise simultaneously to the constituent quark mass.
The last decade has brought detailed lattice data for the primitive vertices of QCD in Landau gauge. A practical use of this data has been to constrain Dyson-Schwinger parametrizations of the most elementary QCD Green's functions, that are now reasonably well known.
With this knowledge of the underlying theory in the infrared regime we attempt to connect the Landau gauge formalism and the constituent quark model to ascertain the relative size of the various possible structures in the quark-antiquark production vertex, including the postulated 3P0 quark-model piece.

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Packing quarks in 9 qubits

Authors: Juan José Gálvez-Viruet[1]; Felipe J. Llanes-Estrada[1]

[1] *Universidad Complutense de Madrid*

Corresponding Author: juagalve@ucm.es

In this ongoing work we show how the quantum numbers of a quark can be packed in nine logical qubits. For this, we are employing one phase for each of the three components of the spatial momentum. As opposed to a lattice calculation, momentum is thus represented in a continuum property of the qubit. The discretization of a hadron system then needs to be effected at the level of the particle number.

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ρ-meson in momentum space : A light-front Hamiltonian approach

Author: Satvir Kaur[1]

[1] *Institute of Modern Physics, Chinese Academy of Sciences, Lanzhou*

Corresponding Author: satvir@impcas.ac.cn

The structure of ρ-meson is investigated through the leading-twist momentum-dependent parton distribution functions within the basis light-front quantized (BLFQ) framework. To begin with, the light-front wavefunctions (LFWFs) are computed by truncating the light-front Hamiltonian to take into account the valence Fock sector and the one containing a dynamical gluon, $|q\bar{q}\rangle$ and $|q\bar{q}g\rangle$. Then, these wave functions are employed to study the *so-called* parton distribution functions (PDFs), which are the one-dimensional functions, in addition to the three-dimensional transverse momentum-dependent parton distribution functions (TMDs). Comparing our predictions with other model results confirm a qualitative consistency for the valence quark PDFs and TMDs. We, further, show some gluon distributions in which ρ-meson does not transfer orbital angular momentum from initial to its final state, that make us investigate the distributions f_1^g, g_{1L}^g, h_1^g and f_{1LL}^g in momentum space.

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Features of hadron structure from basis light-front quantization

Author: Chandan Mondal[1]

[1] *Institute of Modern Physics, Chinese Academy of Sciences*

Corresponding Author: mondal@impcas.ac.cn

Basis light front quantization (BLFQ) is a nonperturbative approach, which has been developed for solving many-body bound state problems in quantum field theories. It is a Hamiltonian formalism incorporating the advantages of the light-front dynamics. In my talk, I will report our recent progress in applying BLFQ to reveal structure of hadrons, specifically the pion and the nucleon. We will discuss various hadronic observables, such as the electromagnetic form factors, PDFs, GPDs, etc., of those hadrons. We will also discuss the gluon distributions, when one dynamical gluon is retained in the systems.

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Charge and magnetization distribution inside the nucleon with Dispersively Improved Chiral EFT

Authors: José Manuel Alarcón[1]; Christian Weiss[None]

[1] *Universidad de Alcalá*

Corresponding Authors: weiss@jlab.org, jmanuel.alarcon@uah.es

The charge and magnetization distribution inside the nucelon are properties of interest to learn about the electromagnetic structure of the ordinary matter. Using light-front dynamics, rooted on the Hamiltonian formulation, we can define unambiguously the distribution of charge and magnetization on the nucleon. These are called the transverse densities. In this talk I will show how using a new formulation of Chiral Effective Field Theory, that includes dispersion theory, we can determine the transverse densities of the nucleon from low energy electron-proton scattering, and learn how the charge and magnetization are distributed inside the nucleon up to short distances.

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Quantum Simulation of Lattice Gauge Theories

Authors: Christopher Winterowd[1]; Michael Fromm[2]; Owe Philipsen[2]

[1] *Goethe University, Frankfurt*

[2] *Goethe University*

Corresponding Author: winterowd@itp.uni-frankfurt.de

Quantum simulations of lattice gauge theories are typically performed in the Hamiltonian formulation of the theory. We briefly discuss the two state-of-the-art approaches for digital quantum simulations, quantum annealing and universal gate-based quantum computing. While the quantum annealer acts as a laboratory for toy models e.g. solving for the ground state or dynamics of small systems - universal gate-based quantum computing promises to have the right resource scaling with system size. In particular, by employing variational quantum algorithms, the latter offers the possibility to study lattice gauge theories coupled to matter in the T-mu plane, for small system sizes on currently available hardware. As a simple illustration, we present work currently being done on Z_2 lattice gauge theory.

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QCD vacuum replicas

Authors: Pedro Bicudo[1]; Emilio Ribeiro[None]

[1] *CeFEMA, IST, Lisboa*

Corresponding Author: pedro3bicudo@gmail.com

A metastable phase has important physical implications, since it may form vacuum bubbles detectable experimentally. It is well known that, due to spontaneous chiral symmetry breaking, there are two, or more, different QCD vacua. In the chiral limit, in the true vacuum, the pseudoscalar ground states are Goldstone bosons. The chiral invariant vacuum (at the top of the "Mexican hat") is an unstable vacuum decays through an infinite number of scalar and pseudoscalar tachyons. Besides, QCD vacuum replicas, an infinite tower of excited vacuum solutions, have been predicted in the Coulomb gauge. It remained to show whether the QCD replicas are metastable or unstable.

We study the spectrum of quark-antiquark systems in the first excited QCD replicas. The mass gap equation for the vacua and the Salpeter-RPA equation for the mesons are solved for a simple chiral invariant and confining model of the Coulomb gauge. We find no tachyons, thus showing the QCD replicas in our approach are indeed metastable. Moreover the energy spectra of the mesonic quark-antiquark systems in the first replicas are close to the one of the true vacuum.

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Confinement, chiral symmetry breaking, and holography: the 3D image of the pion

Authors: Yang Li[1]; James.P. Vary[2]; Pieter Maris[None]

[1] *University of Science and Technology of China (USTC)*

[2] *Iowa State University (ISU)*

Corresponding Authors: leeyoung1987@ustc.edu.cn, jvary@iastate.edu

The lightest meson, the pion, features two faces – one is the elementary Goldstone boson of QCD and the other is the structured bound state of quarks and gluons. To accommodate both in a single light-front wave function in the valence space, we obtain a sum rule by analyzing the conserved axial-vector current and the general structures of the wave functions. Using an analytic model motivated by holography, we show this sum rule is consistent with requirements of chiral symmetry breaking in AdS/QCD. Within this model, we find a remarkable feature of the pion, namely that the density is mostly uniform inside its radius; furthermore, we obtain good agreement with the experimental pion form factor at spacelike momenta.

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From QED atoms to QCD hadrons

Author: Paul Hoyer[1]

[1] *University of Helsinki*

Corresponding Author: paul.hoyer@helsinki.fi

Hadrons are strongly bound, yet their spectra can be classified as for atoms (and molecules). The apparent dominance of the valence ($q\bar{q}$, qqq) components of QCD bound states is paradoxical: The strong gluon field would be expected to generate an abundance of quark and gluon constituents.

The atomic features of hadrons motivates a closer look at the bound state methods of QED. They are based on a perturbative expansion quite unlike that of the perturbative S-matrix. Bound state perturbation theory starts from an approximate bound state (given, e.g., by the Schrödinger equation), whose wave function is non-polynomial in the coupling α. The series may be reordered by shifting powers of α between the initial wave function and its perturbative corrections. The expansion in α (and $\log\alpha$) of physical quantities such as binding energies is nevertheless unique.

QCD expansions starting with freely propagating quarks and gluons (Feynman diagrams) neglect confinement in the in- and out- states. Bound state constituents interact at all times. Valence quark dominance requires instantaneous interactions, which arise when the gauge is fixed over all space at an instant of time. In temporal gauge ($A^0(t,\vec{x}) = 0$) Gauss' law is implemented as a constraint on physical states. The instantaneous positions of the charges determine the longitudinal electric field E_L, which gives a classical instantaneous potential.

The QCD lagrangian does not determine the hadronic scale $\Lambda_{QCD} \simeq 1\ \text{fm}^{-1}$. This scale can be introduced via the temporal gauge fixing mentioned above. The requirement of translation and

rotation symmetry determines E_L uniquely, up to a universal constant Λ of O(α_s^0). Only (globally) color singlet states are allowed when $\Lambda \neq 0$. For $q\bar{q}$ states E_L gives a linear O(α_s^0) potential $V(r) = \Lambda^2 r$. The confining potential for other states ($qqq,\ q\bar{q}g,\ gg$) is likewise uniquely determined.

The O(α_s^0) bound states define the lowest order of a formally exact bound state expansion. Higher Fock states with transversally polarized (propagating) gluons and $q\bar{q}$ pairs are generated as power corrections in α_s by the interaction terms of H_{QCD}. As in any perturbative expansion each order of α_s must incorporate the exact symmetries of the theory, such as Poincaré invariance and unitarity.

Hadron dynamics is simplified at O(α_s^0) but is still non-trivial, due to relativistic effects and hadron loops. Mesons lie on linear Regge trajectories (at small quark masses) and there are features of duality as observed in experiments. Many aspects remain to be investigated [1,2].

[1] Paul Hoyer, "Journey to the Bound States", SpringerBriefs in Physics (Springer, 2021) arXiv:2101.06721 [hep-ph].
[2] Paul Hoyer, "Hadrons as QCD Bound States," in 14th Conference on Quark Confinement and the Hadron Spectrum (2021) arXiv:2109.06257 [hep-ph].

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The Point Form of Relativistic Quantum Mechanics and Quantum Field Theory

Author: Wolfgang Schweiger[1]

[1] *University of Graz*

Corresponding Author: wolfgang.schweiger@uni-graz.at

Among the three prominent forms of relativistic Hamiltonian dynamics introduced by Dirac, the point form is the least popular one. A very attractive feature of the point form is the clear separation of interaction-dependent and interaction-independent Poincare generators, as already noticed by Dirac. The interaction-dependent generators generate the subgroup of space-time translations, whereas the interaction-independent generators are responsible for the subgroup of Lorentz-transformations. The latter fact makes boosts and spin addition simple. The main reason for the minor popularity of the point form is that the quantization hypersurface is curved and not a hyperplane as in the instant and the front form. But as long as one is only interested in relativistic quantum mechanics, i.e. a relativistic invariant quantum theory for a fixed (or at least restricted) number of particles, this does not matter at all. The formal problem is just to find a representation of the Poincare algebra on an appropriate Hilbert space. For interacting systems this is accomplished by means of the Bakamjian-Thomas construction. The resulting interacting theory is relativistic invariant and it allows for instantaneous interactions as well as for particle production and annihilation, if one sets up an appropriate multichannel framework. But it has a drawback: it violates, of course, microcausality and even the weaker requirement of macrocausality (often also termed as cluster separability). The solution of the cluster problem has been formally given by Sokolov and later on by Coester and Polyzou and consists in unitary transformations by means of, so called, packing operators. We will give applications of the point-form approach to the calculation of electroweak hadron form factors within constituent quark models and we will show, how pion-cloud effects can be treated within such a framework. Also the question of cluster-separability restauration will be addressed.

Cluster separability is, of course, no problem if one goes over to a local quantum field theory. But then one has to work with an intrinsic many-body theory. In the canonical formalism one has to cope with a curved quantization hypersurface, if one wants to do point-form quantum field theory. What we were able to show is that one ends up with the usual Fock-space representation of Poincare generators for a free spin-0 and spin-1/2 quantum fields if one quantizes on a space-time hyperboloid using the usual momentum state basis. It can even be shown that one recovers the usual time-ordered perturbation theory. What is still unclear is, whether quantization on a space-time hyperboloid could

be of advantage when solving interacting QFTs. Our insights concerning point-form QFT will be shortly discussed.

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Pressure, shear and energy distributions for a dressed quark in light-front Hamiltonian QCD

Authors: Asmita Mukherjee[None]; Jai More[1]; Sreeraj Nair[2]; Sudeep Saha[3]

[1] *Indian Institute of technology, Bombay*

[2] *Institute of Modern Physics, Chinese Academy of Sciences, China*

[3] *Indian Institute of Technology, Bombay*

Corresponding Authors: sudeepsaha94@gmail.com, asmita@phy.iitb.ac.in, sreeraj@impcas.ac.cn, more.physics@gmail.com

We calculate the contribution to the gravitational form factors (GFFs) for the quark and gluon from the energy-momentum tensor using the light-front Hamiltonian QCD approach. Instead of a proton state, we consider a simple spin-1/2 composite state with a gluonic degree of freedom, namely a quark dressed with a gluon. Using the GFFs, we calculate the quark and gluon contributions to the mechanical properties like the pressure, shear and energy distributions in the dressed quark state.

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State preparation via the quantum Zeno effect and rodeo projection

Author: Thomas Cohen[1]

[1] *University of Maryland*

Corresponding Author: cohen@umd.edu

Many aspects of QCD are currently inaccessible computationally due to sign problems. These can be evaded if sufficiently large reliable quantum computers are developed and these naturally use Hamiltonian formulations. A key problem in quantum computing is the need to prepare the state of interest. This talk will introduce the ideas behind the quantum zeon effect and the newly developed rodeo projection algorithm and show how they can be combined for an extremely efficient algorithm for state preparation on a quantum computer that should be suitable for producing the QCD vacuum (or finite density nuclear matter) at a computational cost that is power law in the volume of the system.

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On the momentum broadening of in-medium jet evolution using a light-front Hamiltonian approach

Authors: Meijian Li[1]; Tuomas Lappi[2]; Xingbo Zhao[None]; Carlos Salgado[1]

[1] *University of Santiago de Compostela*

[2] *University of Jyväskylä*

Corresponding Authors: carlos.salgado@usc.es, meijian.li@usc.es, xbzhao@impcas.ac.cn, tuomas.v.v.lappi@jyu.fi

Following the formalism developed in our preceding works [1], a non-perturbative light-front Hamiltonian approach, we investigated the momentum broadening of a quark jet inside a SU(3) colored medium. We performed the numerical simulation of the real-time jet evolution in the Fock space of |q> + |qg>, at an extensive range of [illegible]+, and various medium densities. With the obtained light-front wavefunctions of the quark jet, we extracted the jet's observables, including its transverse momentum distribution, the quenching parameter, and the gluon emission rate. We analyzed the interplay between the medium-induced gluon emission and the momentum broadening. This work provides an enhanced understanding of jet quenching from non-perturbative perspectives.

[1] M. Li, T. Lappi, and X. Zhao, "Scattering and gluon emission in a color field: A light-front Hamiltonian approach", Phys. Rev. D 104 (2021) no.5, 056014; arXiv:2107.02225 [hep-ph].