

# Light Cone 2021: Physics of Hadrons on the Light Front

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## Book of Abstracts



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**Plenary Session / 1****Simple Light Front Quark Models****Authors:** Jonatan Posigula<sup>1</sup>; Sirajudheen Kuthini Kunhammed<sup>2</sup>; Wayne Polyzou<sup>1</sup><sup>1</sup> *University of Iowa*<sup>2</sup> *None***Corresponding Author:** polyzou@uiowa.edu

I discuss a relativistic light-front model of hadrons based on strong-coupling QCD degrees of freedom that is designed to be simple enough to explore the role of sea quarks in hadronic structure and reaction calculations. The degrees of freedom are confined local and global color singlet systems quarks of antiquarks connected by “strings” represented by confining interactions. These bare singlets interact via a string breaking interaction. The bare singlets have an approximate linear confinement and lie on Regge trajectories. The string breaking interaction makes most of the bare singlets unstable. Like QCD, the scales of the model are set by the quark masses and a single strength parameter. The strings break with approximately equal probability at any point along the line connecting quarks and antiquarks or diquarks. In this model the flavor dependence only enters via the quark masses. The model has several interesting features. First it has dual representations in terms of partonic and hadronic degrees of freedom. The relativistic invariance is exact; including transverse rotations. The wave functions for all bare hadrons can be evaluated analytically and hadronic matrix elements of the string breaking vertex for any combination of initial and final bare hadronic states can also be evaluated analytically. Using the Regge slope of the bare mesons to fix the single strength parameter in the meson sector results in a bare mass spectrum, pi-pi scattering cross section and rho lifetime, and pion form factor that are approximately consistent with experiment. The strength parameter used in the meson sector also gives a consistent picture of the bare mass splittings in the baryon sector. Prediction for sea quark probabilities were investigated for both the pion and proton. The model can also be applied to treat exotic mesons and baryons singlet systems of quarks and diquarks.

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**Parallel Session / 2****Studying electron-positron annihilation into  $K_S K \pi$  and  $K_S K \pi \pi^0$  with the CMD-3 detector (canceled)****Author:** Artem Uskov<sup>1</sup><sup>1</sup> *Budker Institute of Nuclear Physics***Corresponding Author:** arthem.usk+conferences@gmail.com

We studied the process  $e^+e^- \rightarrow K K \pi$  with the CMD-3 detector at the electron-positron collider VEPP-2000. The statistics collected by the CMD-3 detector in the energy range of 1.2–2 GeV during the 2011, 2012, 2017, 2019 runs, with a total luminosity integral of  $\sim 120 pb^{-1}$ , was used for the analysis. The measured cross-section is crucial for the physics of light hadrons from  $u, d, s$  quarks, clarifying the hadronic contribution to the anomalous magnetic moment of the muon  $(g-2)_\mu$ , and independently measuring the resonance parameters of both  $\phi(1680)$ ,  $\rho(1450)$ . The intermediate dynamics of this process is also of interest, allowing us to check the isotopic relations and prove the dominance of the neutral  $K^*(892)$  channel. We developed a novel methodology for selecting signal events. Including multi-staged kinematic reconstruction. By adding the second stage, we reduced the background  $\sim 5$  more times. This stage depends on a rigorous study of the background. Since we identified - the main physical background to be the process  $e^+e^- \rightarrow 4\pi$ .

The outline of the designed steps:

1. Kinematic reconstruction with 4 charged tracks.
2. Track combination, to distinguish the  $K_S$  meson by invariant mass and decay vertex.
3. Restriction on the energy of  $\gamma$  not bound to tracks.
4. Final selection of signal events based on analysis of 2D-distribution of four-track events by energy imbalance  $\Delta E$  and momentum vector sum modulus of all four particles  $\Delta p$ .
5. Simulation to find efficiency  $\varepsilon$  and estimate systematic errors.

So, as a result of this work we not only designed a new selection algorithm, but also studied the theoretical aspect of the cross-section in the Vector Meson Dominance Framework. Therefore, we improved the world precision of  $\phi(1680)$ ,  $\rho(1450)$  and measured the cross-section of  $e^+e^- \rightarrow KK\pi$  with the best accuracy.

**Parallel Session / 3**

## Quarkonium at Belle II

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The Belle II experiment at the SuperKEKB energy-asymmetric  $e^+e^-$  collider is an upgrade of the B factory facility at KEK in Tsukuba, Japan. The experiment began operation in 2019 and aims to record a factor of 50 times more data than its predecessor. Belle II is uniquely capable of studying the so-called “XYZ” particles: heavy exotic hadrons consisting of more than three quarks. First discovered by Belle, these now number in the dozens, and represent the emergence of a new category within quantum chromodynamics. We present recent results in new Belle II data, and the future prospects to explore both exotic and conventional quarkonium physics.

**Parallel Session / 4**

## Flavour physics with electroweak-penguin and semileptonic decays at Belle II

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In the recent years, several measurements of B-decays with flavor changing neutral currents, i.e.  $b \rightarrow s$  transitions hint at deviations from the Standard Model (SM) predictions. In addition there are discrepancies with the SM predictions in  $b \rightarrow c\tau\nu$  decays. The Belle II experiment is a substantial upgrade of the Belle detector and operates at the SuperKEKB energy-asymmetric  $e^+e^-$  collider. The present status of measurements at Belle II related to these so called B anomalies will be presented, including a novel search for the  $B \rightarrow K\nu\bar{\nu}$ ,  $b \rightarrow s$  transition.

**Parallel Session / 5**

## Kaon and pion properties from generalized parton distributions

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How the bulk of the Universe's visible mass emerges and how it is manifest in the existence and structure of hadrons are fundamental questions yet to be answered. Understanding the underlying mechanisms requires being able to explain the structural properties of the pion and kaon. In this talk, we shall discuss many aspects on the internal structure of pion and kaon, as revealed by their corresponding light-front wavefunctions generalized parton distributions (charge, mass and pressure distributions, etc.).

**Parallel Session / 6**

## Proton 3D tomography at low- and moderate- $x$ via TMD gluon densities

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We present exploratory studies of the 3D gluon content of the proton, as a result of analyses on leading-twist transverse-momentum-dependent (TMD) gluon distribution functions, calculated in a spectator model for the parent proton. Our formalism embodies a fit-based parameterization for the spectator-mass density, suited to describe both the small- and the moderate- $x$  regime. Particular attention is paid to the  $T$ -odd gluon TMDs, which represent a key ingredient in the description of relevant spin-asymmetries emerging when the nucleon is polarized, as the gluon Sivers effect. All these analyses are helpful to shed light on the gluon dynamics inside nucleons and nuclei, which is one of the primary goals of new-generation colliders, as the Electron-Ion Collider, the High-Luminosity LHC and NICA-SPD.

**Parallel Session / 7**

## Radial excitations in the constituent quark model

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In recent years, the radial excitations of heavy hadrons have been identified in experiments. Motivated by that, we have studied their decay properties in the nonrelativistic constituent quark model.

It is found that the relativistic correction is essential to explain the large decay width indicating that the relativistic model may be necessary. In this talk, we will discuss our attempt to visit the problem by using the light-front quark model (LFQM) which is based on the relativistic framework.

**Parallel Session / 8**

## Minkowskian three-body model of the proton and Ioffe-time imaging

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Understanding the structure and dynamics of the proton constitute one of the most important challenges in hadron physics. From the theoretical point of view, one of the challenges is to extract from Lattice QCD calculations, performed in Euclidean space, Minkowskian quantities such as the proton parton distribution function. Due to the inherent difficulties associated with the mapping of Euclidean quantities to the corresponding Minkowskian ones, it is advantageous to have a solution defined directly in Minkowski space for calculations of dynamical observables such as momentum distributions.

In this contribution we present results for the proton calculated using a simple but dynamical model defined in Minkowski space [1]. Our starting point is the Bethe-Salpeter-Faddeev equation for a system of three spin-less bosons interacting through a contact interaction. Recently, the solution to this equation was studied in great detail by us in the papers [2, 3, 4]. In this work, the equation is solved in the valence approximation and the parameters of the model are set by comparing the calculated Dirac form factor with experimental data. The single- and double parton distributions of the proton are then computed. The proton image on the null plane in the space given by the transverse coordinates and the Ioffe times  $\tilde{x}_{1,2}$  is also studied, by performing numerically the Fourier transformation of the distribution amplitude.

[1] E. Ydrefors and T. Frederico, arXiv:2108.02146 [hep-ph].

[2] E. Ydrefors, J.H. Alvarenga Nogueira, V. Gigante, T. Frederico and V.A. Karmanov, Phys. Lett. B 770 (2017) 131.

[3] E. Ydrefors, J.H. Alvarenga Nogueira, V.A. Karmanov and T. Frederico, Phys. Lett. B 791 (2019) 276.

[4] E. Ydrefors, J.H. Alvarenga Nogueira, V.A. Karmanov and T. Frederico, Phys. Rev. D 101 (2020) 096018.

**Parallel Session / 9**

## Heavy flavor physics at future Z factories

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The rare Z hadronic decays and heavy flavored decays provides new perspectives to probe the quark sector. Here we propose to study various topics for future colliders working at the Z pole.

The study will also further motivate detector R&D for the FCC-ee, CEPC and other proposed experiments.

**Parallel Session / 10**

## **Analysis of $B \rightarrow K_1 \ell \ell$ channels in an effective field theory approach (canceled)**

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We analyse the rare semileptonic decays of  $B$  meson to axial vector mesons  $K_1(1270)$  and  $K_1(1400)$  mediated by the flavor changing neutral current  $b \rightarrow s \ell \ell$  quark level transition, in an effective field theory approach. We perform a global fit to all the relevant and up-to-date  $b \rightarrow s \ell^+ \ell^-$  data for various sets of (axial)vector couplings. We then look over the implications of the allowed parameter space on the branching ratios and several physical observables such as forward-backward asymmetry, lepton polarization asymmetry and lepton flavor universality violating parameters of  $B \rightarrow K_1 \ell^+ \ell^-$  processes.

**Parallel Session / 11**

## **Multiresolution quantum field theory in light-cone coordinates**

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We analyse the use of wavelet transform in quantum field theory models written in light-cone coordinates. In a recent paper [W.N Polyzou, Phys. Rev. D 101(2020) 096004] the author used  $x^+$  variable as ‘time’, and applied wavelet transform to the ‘spatial’ coordinates only. This makes the theory asymmetric with respect to space and time coordinates. In present contribution we generalize the concept of continuous causal path, which is the basis of path integration, to the sequences of causally ordered space-time regions, and present evaluation rules for Feynman path integrals over such sequences in terms of wavelet transform. Both the path integrals and the wavelet transform in our model are symmetric with respect to the light-cone variables  $(x^+, x^-)$ . The definition of a space-time event in our generalization is very much like the definition of event in probability theory.

**Parallel Session / 12**

## **Threshold resummation for CGC hadron production**

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The talk will include our study on the single hadron inclusive production in the forward rapidity region in proton-nucleus collisions. We find the long-standing negative cross section at next-to-leading-order (NLO) is driven by the large negative threshold logarithmic contributions. We established a factorization theorem for resumming these logarithms with systematically improvable accuracy within the color glass condensate formalism. We demonstrate how the threshold leading logarithmic accuracy can be realized by a suitable scale choice in the NLO results. The NLO spectrums with the threshold logarithms resummed remain positive and impressive agreements with experimental data are observed. And besides the single hadron production, the talk may also contain the results of our recent work: the NLO fixed order calculation of the E distribution of single jet production in pA collisions and the related threshold resummation.

**Parallel Session / 13**

## Production of multi-charmed and exotic hadrons in heavy ion collisions

**Author:** Sungtae Cho<sup>1</sup>**Co-author:** Su Hyoung Lee<sup>2</sup><sup>1</sup> *Kangwon National University*<sup>2</sup> *Yonsei University***Corresponding Author:** sungtae.cho@kangwon.ac.kr

We discuss multi-charmed and exotic hadrons in heavy ion collisions by focusing on their production based on both the statistical and coalescence models. Starting from the investigation on estimated yields of multi-charmed hadrons in the statistical hadronization model, we consider transverse momentum distributions of those hadrons produced at quark-hadron phase transition in the coalescence model. We also consider the yield and the transverse momentum distribution of charmed exotic hadrons such as X(3872) and recently observed Tcc mesons, and furthermore evaluate transverse momentum distribution ratios between various charmed hadrons. We show that the transverse momentum distribution ratios are closely related to the kinds and numbers of quarks as well as the interplay between constituent quarks of those hadrons, and therefore we insist that studying both the transverse momentum distribution and transverse momentum distribution ratios of multi-charmed and exotic hadrons provides us with useful information on hadron production mechanism in heavy ion collisions.

**Parallel Session / 14**

## Un-binned angular analysis of $B \rightarrow D^* l \nu_l$ and the right-handed current

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We perform a sensitivity study of an un-binned angular analysis of the  $B \rightarrow D^* l \nu_l$  decay, including the contributions from the right-handed current. We show that the angular observable can

constrain very strongly the right-handed current without the intervention of the yet unsolved  $V_{cb}$  puzzle.

**Parallel Session / 15**

## Deep learning as a unified model-selection tool

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Experimental results from hadron-hadron scatterings or decays are usually interpreted by using some phenomenological models. The conventional model-fitting scheme cannot give us a definitive answer because different models can give almost similar goodness of fit. In our work, we show that deep learning can be used as a unified model-selection tool. We prepared 35 pole-based models and train the deep neural network to identify the most likely pole configuration of a given experimental data. Using the elastic pion-nucleon scattering as the experimental data, we generate  $10^6$  inference amplitudes and fed them directly to the trained neural network. We found that out of the 35 pole-based models, only 4 models are identified. We also show that the result of inference is independent on the generation of inference amplitudes.

**Parallel Session / 16**

## Forward dijet production at the EIC: beyond the TMD factorization

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Measurements of azimuthal correlations in the production of forward dijets in deep inelastic scattering provide the opportunity to probe the Weizsäcker-Williams gluon transverse momentum dependent (TMD) parton distribution, and the possibility for the discovery of gluon saturation at the future Electron-Ion Collider (EIC). While the TMD factorization is expected to hold near back-to-back production, there are important kinematic (perturbative power) and genuine saturation contributions that must be resummed for more controlled phenomenological predictions.

In this talk, I will compare the results of the TMD and the improved TMD factorization framework to those in the Color Glass Condensate (CGC), and report on the expected size of kinematic and genuine saturation corrections at different kinematics accessible at the EIC [1]. I will discuss recent progress towards the computation of dijet production at the next-to-leading order in the CGC [2], and the possibility of extending the TMD-CGC correspondence to higher orders in perturbation theory.

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Parallel Session / 17

## Light-cone expansion of the amplitudes of FCNC B-decays

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Nonfactorizable corrections induced by charm-quark loops in exclusive FCNC  $B$ -decays (i.e.  $B$ -decays induced by flavour-changing neutral currents) are discussed. We show that a consistent calculation of the appropriate QCD correlation function requires the full generic three-particle distribution amplitude (3DA)  $\langle 0 | \bar{q}(y) G_{\mu\nu}(x) b(0) | B(p) \rangle$  with *non-aligned* arguments: Expanding the latter 3DA amplitude near the light cone, one finds that the  $B$ -decay correlation function is dominated by the regions  $x^2 \sim 0$  and  $y^2 = 0$ , but  $(x - y)^2 \neq 0$ . As the result, for a proper description of the amplitudes of FCNC  $B$ -decays, the full dependence of the 3DA on the variable  $(x - y)^2$  is necessary.

Parallel Session / 18

## Two-photon transitions of charmonia on the light front

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We investigate the two-photon transitions  $c\bar{c} \rightarrow \gamma^* \gamma$  of the charmonium system in light-front dynamics. The light-front wave functions were obtained from solving the effective Hamiltonian based on light-front holography and one-gluon exchange interaction within the basis light-front quantization approach. We compute the two-photon transition form factors as well as the two-photon decay widths for S- and P-wave charmonia  $\eta_c$  and  $\chi_{cJ}$ . Without introducing any free parameters, our predictions are in good agreement with the recent experimental measurements by BaBar and Belle, shedding lights on the relativistic nature of charmonium.

Parallel Session / 19

## Light-front quantization of Maxwell Chern-Simons Higgs theory

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In this talk, I would consider the light-front quantization of the Maxwell Chern-Simons Higgs theory using the Hamiltonian and path integral formulations.

**Parallel Session / 20**

## A light-front supersymmetric field theory

**Author:** Daya Shankar Kulshreshtha<sup>1</sup>

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In this talk, we consider a light-front supersymmetric field theory described by the Wess-Zumino model (WZM) which remains invariant under rigid/global supersymmetry transformations (that rotate bosons into fermions and fermions into bosons). The theory satisfies the super Poincare algebra (SPA) and has a non-manifest supersymmetry (different from the superfield formalism). The instant-form (IF) quantization (IFQ) of the theory is being facilitated due to the fact that  $(\gamma^0)^2 = 1$  even though the theory has fermi fields. However, new problems arise in the light-front (LF) quantization (LFQ) of the theory originating from the fact that  $(\gamma^\pm)^2 = 0$  where  $\gamma^\pm := (\gamma^0 \pm \gamma^3)$ . This difficulty gets resolved if one goes to the formalism of so-called good fermions and the bad fermions (*à la* Mannheim, Lowdon and Brodsky (MLB)) that one defines with the help of the projection operators of the theory ( $\Lambda^\pm := \frac{1}{2}\gamma^0\gamma^\pm$ ). Using this formalism, we study the LFQ of this theory using the Hamiltonian and path integral quantization procedures.

**Plenary Session / 22**

## A Nonperturbative Perspective on the Light-Front Vacuum

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As has been seen in recent calculations for  $\phi^4$  theory, tadpole contributions are important for symmetry-breaking effects and yet are missing from standard light-front calculations, because they require transitions to and from the vacuum. Inclusion of such vacuum transitions also implies contributions from vacuum bubbles. A perturbative calculation can make the distinction and subtract such unwanted bubbles by hand, but a nonperturbative calculation cannot. We propose a method by which vacuum transitions may be included in light-front calculations: momentum-conserving delta functions are replaced with model functions of finite width. This regulates the vacuum-bubble contributions. The vacuum energy can then be subtracted from the eigenenergy of a physical state, followed by the limit of zero width.

**Parallel Session / 23**

## Rotational symmetry in a light-front effective potential

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An effective potential between two fixed sources is computed in light-front quantization for a quenched scalar Yukawa theory. The quenching removes pair-production processes that would result in a spectrum unbounded from below. The sources are fixed with respect to ordinary time, but move in the light-front longitudinal direction. The neutral scalar field is represented by a coherent state, which is obtained nonperturbatively as an eigenstate of the model energy, with the eigenenergy determining the effective potential. Although explicit rotational symmetry is broken by the use of light-front coordinates, the effective potential is rotationally symmetric and matches the standard Yukawa potential for scalar exchange.

**Plenary Session / 24**

## **Generalized Polarizabilities of the Proton: Overview and New Results**

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The Generalized Polarizabilities (GPs) are fundamental properties of the nucleon. They characterize the nucleon's response to an applied electromagnetic field, giving access to the polarization densities inside the nucleon. As such the GPs represent a central path towards a complete understanding of the nucleon dynamics. Previous measurements of the proton electric GP at intermediate four-momentum transfer squared have challenged the predictions of theoretical calculations, raising questions in regard to the underlying reasons responsible for a local enhancement of the electric GP. The measurement of the magnetic GP on the other hand promises to quantify the interplay of the paramagnetism and diamagnetism contributions inside the proton. An overview on this topic, new results from JLab and future prospects will be discussed in this talk.

**Parallel Session / 25**

## **Light front wave functions of mesons from the Dyson-Schwinger/Bethe-Salpeter equations approach**

**Author:** Chao Shi<sup>1</sup>

**Co-authors:** Xurong Chen ; Yaping Xie

<sup>1</sup> *Nanjing University of Aeronautics and Astronautics*

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The light front wave functions (LFWFs) are conventionally obtained by solving the light-cone QCD Hamiltonian. In this talk, I'll demonstrate an alternative approach, which is to extract the leading Fock-state LFWFs (LF-LFWFs) of light and heavy pseudo-scalar and vector mesons from their dynamically solved Bethe-Salpeter wave functions. An important property of these LF-LFWFs is that they imply the existence of considerable higher Fock-states in light mesons. Using these LF-LFWFs, we show the 3D imaging of the mesons with the help of the generalized parton distributions and the transverse momentum dependent PDFs. We will also show that they well produce the diffractive vector meson electroproduction data at HERA within the color dipole model.

## Parallel Session / 26

**Forward quark jet-nucleus scattering in a light-front Hamiltonian approach****Authors:** Meijian Li<sup>1</sup>; Tuomas Lappi<sup>2</sup>; Xingbo Zhao<sup>3</sup><sup>1</sup> *University of Jyväskylä*<sup>2</sup> *University of Jyväskylä*<sup>3</sup> *Institute of Modern Physics, Chinese Academy of Sciences***Corresponding Author:** mliy@jyu.fi

We develop a numerical method to nonperturbatively study scattering and gluon emission of a quark from a colored target using a light-front Hamiltonian approach. The target is described as a classical color field, as in the color glass condensate effective theory. The Fock space of the scattering system is restricted to the  $|q\rangle + |qg\rangle$  sectors, but the time evolution of this truncated system is solved exactly. This method allows us to study the interplay between coherence and multiple scattering in gluon emission. It could be applied both to studying subeikonal effects in high-energy scattering and to understanding jet quenching in a hot plasma.

## Parallel Session / 27

**A study of the  $J/\psi$  baryon-antibaryon decays beyond the leading power accuracy****Author:** Nikolay Kivel<sup>1</sup><sup>1</sup> *Technische Universitaet Muenchen***Corresponding Author:** nik.kivel@tum.de

The  $J/\psi$  decays into octet baryon-antibaryons pairs is studied using the QCD factorisation framework. The power suppressed corrections are calculated for the first time using higher twist baryon light-cone distribution amplitudes. The obtained results are used for a phenomenological analysis of experimental data. It is found that the polarisation parameter  $\alpha_B$  can be described within accuracy 10-30%, which may indicate that the pQCD contribution dominates this observable. The possibility to constrain the baryon DAs from the  $J/\psi$  decays will also be discussed.

## Parallel Session / 28

**Pion structure in Minkowski space****Authors:** Wayne de Paula<sup>1</sup>; Emanuel Ydrefors<sup>1</sup>; Giovanni Salme<sup>2</sup>; Tobias Frederico<sup>1</sup><sup>1</sup> *Instituto Tecnológico de Aeronáutica*<sup>2</sup> *INFN - National Institute for Nuclear Physics***Corresponding Author:** lspwayne@gmail.com

In this talk I will present a dynamical model for the pion based on the solution of the Bethe-Salpeter equation in Minkowski space. For this end, we use the Nakanishi integral representation of the Bethe-Salpeter amplitude. The input of the interaction kernel has the quark and gluon masses, and also a scale parameter related to the extended quark-gluon vertex. Within this model, we obtain the

pion weak decay constant, the valence probability, the LF-momentum distributions, the distribution amplitudes, the probability densities both in the LF-momentum space and the 3D space given by the Cartesian product of the covariant Ioffe-time and transverse coordinates [1]. In addition, we calculated the pion electromagnetic form factor with a good agreement with available experimental data [2].

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**Plenary Session / 29**

## Elementary Example of Exact Effective-Hamiltonian Computation

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An exact computation of effective Hamiltonians in an elementary model akin to quantum field theory is carried out by solving equations of the renormalization group procedure for effective particles (RGPEP) [1]. The computation exhibits the mechanism by which the weak-coupling expansion and Tamm-Dancoff approximation increase in accuracy along the RGPEP evolution. The model computational pattern can be followed in perturbative computations of effective Hamiltonians in realistic theories.

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**Plenary Session / 30**

## Light-Front Quantization from Then Until Now

**Author:** Philip Mannheim<sup>1</sup>

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We trace the development of light-front quantization from its infinite momentum frame origin to its current formulation. We emphasize its difference from the infinite momentum frame approach especially in regard to vacuum loop diagrams. We identify the importance of off mass shell light-front contributions, especially in regard to circle at infinity contributions to vacuum Feynman diagram contours. We compare and contrast the instant-time and light-front quantization procedures and their respective Hamiltonians, and determine what we mean by non-relativistic in the light-front case. We show that the relativistic eikonal approximation should be formulated in light-front coordinates rather than in instant-time ones.

**Plenary Session / 31**

## Nucleon Structure Modification from Tagged DIS Measurements at JLab and the EIC

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Understanding the origin of the EMC effect - the modification of the internal structure of nucleons bound in nuclei - is an ongoing effort in QCD research with far-reaching implications for our understanding of the fundamental structure of matter. Inclusive measurements have characterized many features of the EMC effect, but are insensitive to the initial state of the nucleus and therefore limited in their ability to pinpoint the mechanisms driving nucleon modification. Recently emerging measurements of tagged deep inelastic scattering (TDIS) from atomic nuclei probe the dependence of quark distribution functions on the initial state of the bound nucleon. The backward angle neutron detector (BAND) was built to measure TDIS off highly-virtual protons in deuterium with the detection of high-momentum spectator neutrons. This novel measurement is sensitive to the bound proton's structure as a function of its initial momentum within the nucleus. This talk will present preliminary results from BAND, which will further our understanding of the EMC effect and its relation to short-range correlations in nuclei. Given time I will present studies of the ability to extend these studies to the EIC.

**McCartor Session / 32**

## State-of-the-art extractions of pion parton distributions

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Recently, we have performed a Monte Carlo global QCD analysis of pion parton distribution functions using Drell-Yan and leading neutron data. Since then, we have systematically implemented threshold resummation on the Drell-Yan cross section using various methods of the calculation, each of which differently impacts the large  $x$  distribution of the valence quark. Additionally, we have performed fits of the valence distribution to available lattice QCD data in the form of reduced pseudo Ioffe time distributions. Impact studies for the future EIC were performed. Venturing into the 3-dimensional structure of the pion, we also look at low-transverse momentum data to constrain the pion transverse momentum dependent parton distribution functions. In this talk, I will highlight these topics in the latest on pion structure global analyses.

**Plenary Session / 33**

## Hadron Mass in the Medium

**Author:** Su Hounng Lee<sup>1</sup>

<sup>1</sup> *Yonsei University*

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I will first review several topics in hadron mass and chiral symmetry restoration. Then I will discuss the current status of hadron mass shift measurements in nuclear medium. Finally, I will discuss some recent suggestions on  $K_1$  and  $K^*$  meson mass measurements both in heavy ion collision and nuclear target experiments.

**Plenary Session / 34****QCD Analysis of Pion Parton Distributions****Author:** Wally Melnitchouk<sup>1</sup><sup>1</sup> *Jefferson Lab***Corresponding Author:** wmelnitc@jlab.org

We present recent results from the JAM (Jefferson Lab Angular Momentum) Collaboration's global QCD analysis of pion parton distributions. In particular, we assess the impact of threshold resummation on the behavior of the pion's valence distributions at large parton momentum fractions  $x$ .

**Parallel Session / 35****Effects of bulk viscous medium: quarkonium spectral functions,  $\psi'/J/\psi$  ratio and  $R_{AA}$** **Author:** Lata Thakur<sup>1</sup>**Co-author:** Yuji Hirono<sup>1</sup><sup>1</sup> *APCTP***Corresponding Author:** lata.thakur@apctp.org

We will discuss the effects of bulk viscous quark gluon plasma medium on the quarkonium spectral functions. The bulk viscous correction is incorporated in the distribution functions of thermal quarks and gluons, with which we compute the dielectric permittivity. The modified dielectric permittivity is used to calculate the in-medium heavy quark potential. Using the modified heavy quark complex potential, we compute the quarkonium spectral functions by solving the Schrödinger equation. We fit the spectral functions with the skewed Breit-Wigner form and compute the physical properties of quarkonia such as masses, binding energies, decay widths and also the integrated area under the bound states peak. To discuss the physical implications of our results, we will show the effects of bulk viscous correction on the physical observables such as relative production yield  $\psi'/J/\psi$  ratio and  $R_{AA}$  at the LHC energies.

**Plenary Session / 36****Frame Dependence of Relativistic Charge Distributions****Author:** Cédric Lorce<sup>1</sup><sup>1</sup> *Ecole polytechnique***Corresponding Author:** cedric.lorce@polytechnique.edu

We review and revisit the concept of charge distribution in the relativistic context. Adopting a phase-space perspective allows us to discuss the momentum dependence of these distributions and to connect the well-known pictures in both the Breit frame and the infinite-momentum frame. In particular, we explain why the center of the neutron charge distribution appears to be negative in the infinite-momentum frame and positive in the Breit frame.

Plenary Session / 37

## Novel Hadron Physics by Structure Functions of Spin-1 Hadrons

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There are new polarized structure functions, which do not exist for the spin-1/2 nucleons, in a spin-1 hadron such as the deuteron. In the charged-lepton deep inelastic scattering, the new leading-twist structure functions are  $b_1$  and  $b_2$ , which are related by the Callan-Gross type relation  $b_2 = 2xb_1$  in the Bjorken scaling limit. There exists a parton-model sum rule for  $b_1$  [1]. We theoretically calculated  $b_1$  by using the standard convolution model for the deuteron with D-state admixture [2], and we obtained a very different distribution from HERMES data. This fact indicates that a new hadron-physics mechanism could be needed to explain the large difference. This topic will be investigated at the Jefferson Laboratory, and also at hadron accelerator facilities such as Fermilab by the proton-deuteron Drell-Yan process [3] and the nuclotron-based ion collider facility (NICA) by the  $J/\psi$  production [4].

Second, the gluon transversity is a new and interesting distribution in the spin-1 deuteron. Although there was recent experimental progress on quark transversity distributions, there is no experimental information on the gluon transversity. The gluon transversity does not exist for the spin-1/2 nucleons due to the helicity-conservation constraint. One needs a hadron with spin more than or equal to one, so that the helicity flip of two units is allowed. In our work, we proposed the possibility for finding the gluon transversity at hadron-accelerator facilities, especially in the proton-deuteron Drell-Yan process, by showing theoretical formalism and numerical results [5]. Since the internal spin-1/2 nucleons within the deuteron cannot contribute directly to the gluon transversity, it is a good observable to find a new non-nucleonic component beyond the simple bound system of nucleons in nuclei.

Third, we explain possible transverse-momentum-dependent parton distribution functions (TMDs) for spin-1 hadrons up to twist 4 by decomposing a quark correlation function with the conditions of the Hermiticity and parity invariance [6]. We found 30 new structure functions in the twist 3 and 4 in our work. Since time-reversal-odd terms of the collinear correlation function should vanish after integrals over the partonic transverse momentum, we obtained new sum rules for the time-reversal-odd structure functions,  $\int d^2k_T g_{LT} = \int d^2k_T h_{LL} = \int d^2k_T h_{3LL} = 0$ . In addition, we indicated that new fragmentation functions exist in tensor-polarized spin-1 hadrons. Integrating the TMDs over the transverse momentum, we found new collinear PDFs for spin-1 hadrons. For these PDFs, we showed that a twist-2 relation and a sum rule exist for the tensor-polarized parton distribution functions  $f_{1LL}$  and  $f_{LT}$  [7]. Furthermore, we indicated that four twist-3 multiparton distribution functions  $F_{LT}$ ,  $G_{LT}$ ,  $H_{LL}^\perp$ , and  $H_{TT}$  exist for tensor-polarized spin-1 hadrons.

In the near future, we expect that physics of spin-1 hadrons will become a popular topic, since there are experimental projects to investigate spin structure of the spin-1 deuteron at the Jefferson Laboratory, the Fermilab, the NICA, the LHCspin, and the electron-ion colliders in US and China in 2020's and 2030's.

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**Parallel Session / 38****Nonfactorizable contribution of charming loop to  $B_s \rightarrow \gamma\gamma$  decay****Authors:** Ilia Belov<sup>1</sup>; Alexander Berezhnoy<sup>2</sup>; Dmitri Melikhov<sup>3</sup><sup>1</sup> *M.V. Lomonosov Moscow State University*<sup>2</sup> *M.V. Lomonosov Moscow State University (RU)*<sup>3</sup> *HEPHY, Vienna, Austria and SINP, Moscow, Russia***Corresponding Author:** ilia.belov@cern.ch

In this talk we discuss the nonfactorizable charm-loop effect in the rare FCNC decay  $B_s \rightarrow \gamma\gamma$ . The nonfactorizable contribution comes from the soft gluon emission from c-quark loop. The rigorous calculation requires the knowledge of three particle DA with three independent coordinates. We properly study the influence of three particle DA form on the amplitude by the case of  $B_s \rightarrow \gamma^*\gamma^*$  decay. The numerical estimations are presented for  $B_s \rightarrow \gamma\gamma$  decay branching.

**Parallel Session / 39****Constraining gluon helicity distributions in proton****Authors:** Wally Melnitchouk<sup>1</sup>; Yiyu Zhou<sup>2</sup>; nobuo sato<sup>3</sup><sup>1</sup> *Jefferson Lab*<sup>2</sup> *South China Normal University*<sup>3</sup> *jlabs***Corresponding Author:** zyy.registry@gmail.com

We made simultaneous extraction of spin averaged and spin dependent PDFs within multistep MC procedures, with combined analysis of inclusive unpolarized and polarized jets from RHIC to Tevatron energies. By analyzing the preliminary results we had, we were able to discuss impact of theory assumptions on  $\Delta g$ .

**Parallel Session / 40****The cluster effective field theory for nuclear reactions****Author:** Shung-Ichi Ando<sup>1</sup><sup>1</sup> *Sunmoon University***Corresponding Author:** shungichi.ando@gmail.com

We discuss an application of the cluster effective field theory (EFT) to nuclear reactions at low energies. A target reaction of the present talk is the  $E1$  transition of radiative  $\alpha$  capture on  $^{12}\text{C}$ , which is a fundamental reaction in nuclear-astronomy. We review our recent works to construct the cluster EFT for the reaction, fix some of the coupling constants of the effective Lagrangian by using the elastic  $\alpha$ - $^{12}\text{C}$  scattering data, and calculate the  $E1$  transition rate of the radiative alpha capture rate at the Gamow-peak energy,  $T_G = 0.3$  MeV. We also review a calculation of  $\beta$  delayed  $\alpha$  emission from  $^{16}\text{N}$  and discuss possible applications of the present approach to other reactions.



**Plenary Session / 41****A perturbative expansion for bound states****Author:** Paul Hoyer<sup>1</sup><sup>1</sup> *Helsinki University***Corresponding Author:** paul.hoyer@helsinki.fi

Bound states are perturbatively expanded in the coupling  $\alpha$  around lowest order bound states, not around free states as for scattering amplitudes. The expansion is not unique, as bound state wave functions are non-polynomial in  $\alpha$  even in a first approximation. I describe a first-principles, equal-time method based on a Fock expansion where the constituents are bound by the instantaneous interaction of temporal gauge. The expansion starts from the (bound) valence Fock state of QED atoms and QCD hadrons in any frame. An  $O(\alpha_s^0)$  confining potential arises from a homogenous solution of the QCD gauge constraint [1,2].

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**Parallel Session / 42****ATLAS results on charmonium production and  $B_c$  production and decays****Author:** Semen Turchikhin<sup>1</sup>**Co-author:** ATLAS Collaboration<sup>1</sup> *Joint Institute for Nuclear Research***Corresponding Author:** semen.turchikhin@cern.ch

Recent results from the proton-proton collision data taken by the ATLAS experiment on charmonium production and on  $B_c$  production and decays will be presented. The measurement of the associated production of the  $J/\psi$  meson and a gauge boson, including the separation of single and double parton scattering components, will be discussed. The measurement of  $J/\psi$  and  $\psi(2S)$  differential cross sections will be reported as measured on the whole Run 2 dataset. The measurement of the differential ratios of the  $B_c^+$  and  $B^+$  production cross sections at 8 TeV will also be shown. New results on the  $B_c$  decays to  $J/\psi D_s^{(*)}$  final states obtained with the Run 2 data at 13 TeV will be detailed.

**Parallel Session / 47****Interpolating conformal algebra between the instant form and the front form of relativistic dynamics****Authors:** Chueng Ji<sup>1</sup>; Harleen Dahiya<sup>2</sup>; Hariprashad Ravikumar<sup>3</sup><sup>1</sup> *North Carolina State University, Raleigh, North Carolina 27695, USA*<sup>2</sup> *Dr. B.R. Ambedkar National Institute of Technology, Jalandhar, 144011, India*<sup>3</sup> *New Mexico State University*

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The instant form and the front form of relativistic dynamics introduced by Dirac in 1949 can be interpolated by introducing an interpolation angle parameter  $\delta$  spanning between the instant form dynamics (IFD) at  $\delta = 0$  and the front form dynamics, which is now known as the light-front dynamics (LFD) at  $\delta = \frac{\pi}{4}$ . We extend the Poincaré algebra interpolation between instant and light-front time quantizations (C.-R. Ji and C. Mitchell, Phys. Rev. D 64, 085013 (2001)) to the conformal algebra. Among the five more generators in the conformal algebra, only one generator known as the dilatation is kinematic for the entire region of the interpolation angle ( $0 \leq \delta \leq \frac{\pi}{4}$ ). We find that one more generator from the Special Conformal Transformation (SCT) becomes kinematic in the light-front limit ( $\delta = \frac{\pi}{4}$ ), i.e. the LFD.

**Parallel Session / 48**

## Light-front dynamic analysis of the transition form factors in 1 + 1 dimensional scalar field model

**Authors:** Bailing Ma<sup>1</sup>; Chueng-Ryong Ji<sup>1</sup>

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We investigate the “scalar pion”  $\rightarrow \gamma^* \gamma^*$  transition form factor for the two emitted virtual photons of momentum squares  $q^2$  and  $q'^2$  in both space-like and time-like regions. In 1+1 dimensional scalar field model, we use the direct method in the light-front dynamics (LFD) to access the time-like region without resorting to analytic continuation. In particular, we define the contributions from individual  $x^+$ -ordered amplitudes in LFD to the form factor in a novice way applying both the plus and minus components of the current and confirm that the individual  $x^+$ -ordered amplitudes are dependent on the component of the current taken for the computation while the sum of all the contributions is the same as it must be. We present the analytic result for the one-loop triangle diagram covering the whole ranges of  $q^2$  and  $q'^2$ , both from a manifestly covariant calculation and from the LFD calculation, and show that the end result is identical. We also verify that this analytic result satisfies the dispersion relation in the entire  $q^2$  and  $q'^2$  ranges.

**McCartor Session / 50**

## Lensing function relation in hadrons

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The parton structure is studied using mainly two types of hard scattering processes: exclusive processes, which give access to Generalized Parton Distributions (GPDs), and semi-inclusive processes, described in terms of Transverse Momentum Dependent parton distributions (TMDs). In full QCD, no relations exist between GPDs and TMDs. However, a connection between T-odd effects related to TMDs and GPDs was found in simple models. This relation is commonly referred to as lensing relation. With the tools provided by light-front quantization, I will discuss the features of the models that allow to establish the lensing relation. I will also specify the general discussion to two relevant

examples: the pion, viewed as a prototype of a two-body bound system in the Fock-state representation, and the proton, as the preferential three-body hadron. I will show how, under specific conditions, the pion GPDs and TMDs present a non-trivial relation, and I will emphasize how these conditions are broken in a many-body system.

**Plenary Session / 52**

## Photon-to-Nucleon Transition Distribution Amplitudes and Backward Time-like Compton Scattering

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Nucleon-to-meson and nucleon-to-photon transition distribution amplitudes (TDAs) arise in the collinear factorized description of a class of hard exclusive reactions characterized by the exchange of a non-zero baryon number in the cross channel. In this talk, we review the properties of nucleon-to-photon (and photon-to-nucleon) TDAs, which encode the photon content of the nucleon and allow a new tomography of the nucleon. We present the application of the collinear QCD factorization framework involving photon-to-nucleon TDAs to the description of the exclusive photoproduction off a nucleon of a large invariant mass lepton pair in the backward region. We consider modeling of photon-to-nucleon TDAs relying on the vector-meson-dominance framework and provide estimates of the backward time-like Compton scattering cross-section for the JLab experimental setup. The background due to the electromagnetic Bethe-Heitler process is shown to be negligible in the relevant kinematical regime.

**Parallel Session / 53**

## Two Schrodinger-like equations for hadrons

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In this talk, I will argue that the light-front holographic Schrodinger Equation and the 't Hooft Equation are complementary to each other in governing the transverse and longitudinal dynamics of colour confinement in hadrons. Together, they predict remarkably well the light, heavy-light and heavy-heavy hadrons spectroscopic data, with a universal confinement scale in the holographic Schrodinger Equation. In heavy-heavy hadrons, the confinement scales of the two equations coincide, reflecting the restoration of 3-dimensional rotational symmetry.

**Parallel Session / 54**

## A new Wilson-line based light-cone Lagrangian for gluodynamics

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**Co-authors:** Anna Stasto<sup>2</sup>; Piotr Kotko<sup>1</sup>

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We derive a new classical action for gluodynamics by canonically transforming the light cone Yang-Mills action, where the solutions to the field transformations are directly related to the straight infinite Wilson line functionals defined on the constant light-cone time  $x^+$ . One of the key features of the new action is that it has no triple gluon vertices, because they have been effectively resummed inside the Wilson lines. The lowest order vertex is the four-point MHV vertex. In general, any  $n$ -leg vertex has  $2m - n - 2$  negative helicity legs. Thus the number of diagrams required to compute tree amplitudes is greatly reduced. We have checked that the action reproduces standard results by calculating tree amplitudes up to 8-point Next-to-Next-to-MHV amplitude and found agreement with the standard methods.

Based on H. Kakkad, P. Kotko, A. Stasto JHEP07(2021)187.

**Parallel Session / 55**

## Simulation of nuclear physics on near-term quantum computers using basis light-front quantization

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The light-front quantization provides a natural framework for digital quantum simulation of quantum field theory. In our previous work (2002.04016, 2105.10941), we demonstrated this by developing quantum algorithms based on simulating time evolution and adiabatic state preparation. Aiming for near-term devices, in my talk I will explain how to formulate the relativistic bound state problem as an instance of the Variational Quantum Eigensolver (VQE) algorithm using the Basis Light-Front Quantization (BLFQ) technique (2011.13443, 2009.07885). Having much in common with ab initio quantum chemistry and nuclear theory, the BLFQ formulation provides an ideal framework for benchmarking NISQ devices and testing existing algorithms on physically relevant problems such as the calculation of hadronic spectra and parton distribution functions.

**Parallel Session / 56**

## Masses of hadrons in the chiral symmetry restored vacuum

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We calculate the masses of the vector and axial-vector mesons, as well as the nucleon and the delta resonance in the chiral symmetry, restored vacuum. This is accomplished by separating the quark operators appearing in the QCD sum rules for these hadrons into the chiral symmetric and symmetry breaking parts depending on the contributions of the fermion zero modes. We then extract the vacuum expectation values of all the separated parts of the quark operators using the QCD sum rule relations for these hadrons with their vacuum masses and widths. By taking the chiral symmetry breaking parts to be zero while keeping the symmetric operators to their vacuum values, we obtain the chiral symmetric part of the hadron masses. We find that the masses of chiral partners, such as the  $(\rho, a_1)$  and  $(K^*, K_1)$ , become degenerate to values between 500 and 600 MeV in the chiral symmetry restored vacuum, while parity partners  $(\omega, f_1)$  that are chiral partners only in the limit where the disconnected diagrams are neglected remain non-degenerate with masses (655, 1060) MeV, respectively. The masses of the nucleon and the Delta are also found to reduce to about 500 and 600 MeV, respectively, in the chiral symmetric vacuum. This shows that while chiral symmetry breaking is responsible for the mass difference between chiral partner, both the meson and baryon retain non-trivial fraction of their masses in the chiral symmetry restored vacuum.

**Parallel Session / 57**

## Doubly heavy tetraquarks, $qq'\bar{Q}\bar{Q}'$ , in a nonrelativistic quark model with a complete set of harmonic oscillator bases

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We improve our previous variational method based nonrelativistic quark model by introducing a complete set of three-dimensional harmonic oscillator bases as the spatial part of the total wave function. After fitting to the masses of the ground state hadrons, we apply our new method to analyzing the doubly heavy tetraquark states  $qq'\bar{Q}\bar{Q}'$ . In particular, we compare the result for  $T_{cc}$  to the result in the recent discovery at LHCb. We also calculate the ground state masses of  $T_{sc}(ud\bar{s}\bar{c})$  and  $T_{sb}(ud\bar{s}\bar{b})$  with  $(I, S) = (0, 1), (0, 2)$ . We find that  $T_{bb}(ud\bar{b}\bar{b})$  and  $us\bar{b}\bar{b}$ , both with  $(I, S) = (0, 1)$ , are stable against the two lowest threshold meson states with binding energies  $-145$  MeV and  $-42$  MeV, respectively. We further find that  $T_{cb}(ud\bar{c}\bar{b})$  is near the lowest threshold. The relative positions of the quarks in the tetraquark structure are also discussed.

**Parallel Session / 58**

## Interpolating Lorentz force equation and solution between the instant form dynamics and the light-front dynamics

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When the electromagnetic field is applied to a charged particle, the particle motion is described by the Lorentz force equation which reveals the connection between the electromagnetic field strength tensor and the Lorentz transformation generators represented by the boost and the rotation. We interpolate the Lorentz force equation between the instant form dynamics and the light-front dynamics and investigate the utility of the interpolation in solving the Lorentz force equation. We

discuss how effectively the interpolation can gauge the effect of the kinematic generators saving dynamical efforts in solving the Lorentz force equation. We present how the interpolation can be utilized to enhance and suppress the kinematic and dynamic portion of the electromagnetic fields, respectively, and exemplify its effectiveness by discussing the link between the electromagnetic field strength tensor and the Lorentz transformation generators.

Plenary Session / 59

## Jet Physics Program at RHIC

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Jets are produced in heavy-ion and nucleon-nucleon collisions from hard-scattered patrons of the incoming beams. We can infer the property of hot-dense QCD matter, known as Quark-Gluon Plasma (QGP), by studying the modified jet properties in heavy-ion collisions to their vacuum reference. Relativistic Heavy-Ion Collider (RHIC), at BNL, New York, USA, can collide heavy-ions (like Au+Au and other species) up to the center of mass energy 200 GeV, and proton-proton up to 500 GeV. These collision systems provide a unique opportunity to study the finite temperature QCD medium created in heavy-ion collisions and its vacuum expectations in p+p collisions. I will shed light on the discovery of jet-quenching during the early RHIC accelerator operation and the recent progress that provides a deeper understanding of the medium-induced parton energy loss at RHIC energy. Furthermore, p+p collisions data are analyzed to study the QCD parton shower and jet evolution in a vacuum environment. In the coming years, ongoing STAR and a new upcoming sPHENIX experiments plan to take high luminosity data to have dedicated high precision jet measurements to study the hot-dense and cold QCD medium and its vacuum expectation.

Plenary Session / 60

## Experimental TDA Program at FAIR, JLab and J-PARC

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Hard exclusive processes are a well established tool to study the 3D nucleon structure. The QCD factorisation mechanism in the “nearly forward region” ( $t/Q^2$  small) can be divided into a hard part, described by perturbative QCD (pQCD) and in two general structure functions, the Generalized Parton Distributions (GPDs) for the nucleon and the pion Distribution Amplitudes (DAs), describing the complex non perturbative structure of these particles. In the “nearly backward” kinematic region ( $u/Q^2$  small) the potentially applicable collinear factorized description in terms of a convolution of the non-perturbative nucleon to pion Transition Distribution Amplitudes (TDAs), the nucleon DAs and the hard interaction amplitude from pQCD is assumed to be valid. The scattering under backward angles provides complementary information for studies of the hadron structure, but has been so far less extensively studied than the forward angle case. Therefore, it provides new experimental and theoretical opportunities to gain insights into the 3D structure of the nucleon. The talk will give an overview on recent  $u$ -channel measurements at JLab which provide first hints for the factorisation of the TDA mechanism and discuss them in the context of the TDA model. As an outlook, plans and perspectives for upcoming measurements at JLAB, PANDA at FAIR and J-PARC will be discussed in the context of advancing our understanding of  $u$ -channel physics and gaining new insights into the nucleon structure.

**Parallel Session / 61****Baryonic matter equation of state and the baryons in baryonic matter****Author:** Nam-Yong Ghim<sup>1</sup>**Co-authors:** Hyun-Chul Kim<sup>1</sup>; Ghil-Seok Yang<sup>2</sup>; Ulugbek Yakhsheiv<sup>1</sup><sup>1</sup> *Inha University*<sup>2</sup> *Hoseo university***Corresponding Author:** namyong.ghim@gmail.com

Within the context of the in-medium modified chiral soliton model, we present a recent results for the characteristics of baryonic matter. The model's intrinsic parameters are derived by reproducing nuclear matter properties near the saturation density and fitted by using nuclear phenomenology at the nonstrange sector. We obtain an equation of state that is consistent with numerous phenomenological investigations. We also look at how the masses of low-lying SU(3) baryons including heavy baryons, alter in different baryonic settings.

**Parallel Session / 62****Nucleon quasi-parton distribution functions in the large  $N_c$  limit****Authors:** Hyeon-Dong Son<sup>1</sup>; Polyakov Maxim V.<sup>2</sup>; Tandogan Asli<sup>2</sup><sup>1</sup> *CENuM, Korea University*<sup>2</sup> *Ruhr-University Bochum***Corresponding Author:** hdson@korea.ac.kr

We present our recent studies on the quasi-parton distribution functions in the nucleon within the chiral quark-soliton model. We discuss the properties of the isoscalar unpolarized and isovector polarized quasi-PDFs in the large  $N_c$  limit, such as the generalized sum-rules and the nucleon momentum evolutions. From the model calculations, we observe that the isoscalar unpolarized quasi quark distribution requires careful treatment, especially at small  $x$  region.

**Plenary Session / 63****Abel Tomography: Charge and Energy-Momentum Tensor Densities of the Nucleon****Authors:** Hyun-Chul Kim<sup>1</sup>; June-Young Kim<sup>2</sup><sup>1</sup> *Inha University*<sup>2</sup> *Ruhr-University Bochum***Corresponding Author:** hchkim@inha.ac.kr

Usual three-dimensional (3D) densities of the nucleon are only meaningful quasi-probabilistically through the Wigner distributions. Taking the infinite-momentum frame, where the nucleon is on the light cone, we can define two-dimensional (2D) distributions of the nucleon, which contain the quantum-mechanically probabilistic meaning. The Abel transformations, on the other hand, allow

one to derive the 2D distributions of the nucleon directly from the 3D ones. We will address current investigations on the charge and energy-momentum-tensor (EMT) distributions of the nucleon in this talk, based on the Abel transformations. We first explain how the form of the 2D transverse charge distribution of the polarized nucleon changes as the longitudinal momentum of the nucleon grows from the rest frame to the infinite-momentum frame. Then, we show that the 2D transverse charge and magnetization densities of the proton and neutron can be derived directly from the 3D ones by employing the Abel transformations. We also demonstrate that the EMT densities, i.e., energy, spin, pressure, and shear-force densities in the transverse plane can be obtained by the Abel transforms of the corresponding 3D densities.

**Parallel Session / 64**

## Test of intrinsic charm from Z boson production accompanied by $c$ jet in pp collisions at LHC

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A brief overview of the experimental evidence for the non-zero intrinsic charm (IC) contribution to the proton PDF is presented. The effect of intrinsic heavy quarks on the production of vector bosons accompanied by  $c$  and  $b$  jets in  $pp$  collisions at the LHC is then investigated. The calculations are performed within the combined QCD approach, based on  $k_T$ -factorization at small transverse momenta and the use of collinear QCD factorization for the production of Z-bosons and heavy quark jets at large  $p_T$ . It is shown that the CMS data on the  $p_T$  spectra of Z and a charm-jet can be satisfactorily described in the rapidity region  $|y| \leq 2.5$  without inclusion of the IC components. However, in the forward kinematical region,  $1.5 \leq |y| \leq 2.5$ , the IC signal becomes sizable at  $p_T > 100$  GeV/ $c$ . We also predict a significant enhancement in the distribution of charm jets as a function of  $\Delta y = |y_Z - y_c|$ , where  $y_Z$  and  $y_c$  are the rapidities of the Z-boson and the charm jet, respectively. Moreover, it is shown that charm jet production increases significantly at  $x_F > 0.2$  when the IC component in the proton PDF is taken into account. We also highlight tests of the  $c(x)$  vs.  $\bar{c}(x)$  intrinsic charm asymmetry predicted by LGTH.

**Parallel Session / 65**

## Accessing the coupled-channels dynamics using femtosopic correlations with ALICE at LHC

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Systems as  $K^-p$  and baryon-antibaryon ( $B\bar{B}$ ) are both characterised by the presence, already at the production threshold, of strong inelastic channels which can affect the properties and the formation of bound states and resonances. In the  $\bar{K}N$  system, the  $\Lambda(1405)$  arises from the interplay between the  $\bar{K}N$  and the coupled  $\Sigma\pi$  channel. Experimental constraints on the different  $\bar{K}N$  coupled-channels are needed to provide a full description of the nature and properties of the  $\Lambda(1405)$ . Similarly, baryon-antibaryon systems are characterised by the dominant contribution of several mesonic channels related to the presence of annihilation processes acting below 1 fm. The possible existence of baryon-antibaryon bound states is still under debate due to a limited amount of data for the  $p - \bar{p}$  system available, and either scarce or absent experimental data for  $B\bar{B}$  systems containing strangeness. The femtoscopy technique measures the correlation of particle pairs at low relative momentum.



This method applied in small colliding systems, as pp and p-Pb collisions at ALICE provided high-precision data on several baryon-baryon and meson-baryon pairs showing a great sensitivity to the underlying strong potential and to the introduction of the different coupled-channels. In this talk, we will present femtoscopic correlations measured by ALICE in pp collisions at  $\sqrt{s} = 13$  TeV, separately for data samples obtained with minimum-bias and high-multiplicity triggers, and in peripheral and ultra-peripheral p-Pb and Pb-Pb collisions at  $\sqrt{s} = 5.02$  TeV. In particular, we will show results on the  $K^-p$  correlation function which for the first time provide experimental evidence of the opening of the coupled isospin breaking channel  $\bar{K}^0 - n$  and on the  $\Sigma\pi$  channel contributions. Finally, results from baryon-antibaryon pairs ( $p\bar{p}$ ,  $p-$  and  $-$ ) will be shown for the first time. The effect of annihilation channels on the correlation function and a quantitative determination of the inelastic contributions in the three different pairs will be discussed.

Parallel Session / 66

## Anatomy of nucleon self-energy from equal-time to light-front

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Light-front dynamics (LFD) has been of particular interests in hadron physics with the effort of developing the 3D femtography of the nucleon. In this respect, it is important to trace the instantaneous contribution to the fermion propagator in the LFD which involves the constraint degrees of freedom of the fermion. Interpolating the ordinary instant form dynamics (IFD) to the LFD in quantum electrodynamics [1], we have previously identified that the instantaneous contribution to the fermion propagator in the LFD corresponds to the backward moving fermion propagator in the IFD. In this presentation, we discuss this correspondence between the IFD and the LFD in the loop level analyzing the pion loop contribution to the nucleon self-energy in the chiral effective theory. Specifically, we calculate the backward and forward nucleon self-energy interpolating between the IFD and the LFD and trace each part of the contributions to correspond with the light-front instantaneous (LFI) contribution and the on-mass-shell (OMS) contribution in the LFD. The nonanalytic behavior of the pion loop contribution in the nucleon self-energy is anatomically analyzed to confirm the correspondence of each part between the IFD and the LFD unambiguously. Our numerical results exhibiting the entire profile of the interpolating parameter and the momentum ( $p^z$ ) dependence of the forward and backward moving parts further clarify any conceivable confusion in the prevailing notion of the equivalence between the LFD and the infinite momentum frame ( $p^z \rightarrow \infty$ ) approach in the IFD. We also discuss the light-front zero-mode issue contrasting the results in  $p^z \rightarrow \infty$  and  $p^z \rightarrow -\infty$ .

[1] C.-R.Ji, Z.Li, B. Ma and A. Suzuki, Phys. Rev. D98, 036017(2018)

Parallel Session / 67

## Light-cone distribution amplitudes of the nucleon

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In this talk, we present recent results of the leading-twist distribution amplitudes for the nucleon and  $\Delta$  baryon within the framework of the chiral quark-soliton model. We first construct the light-cone wave functions to the five-quark state. By employing them, we then obtain the distribution amplitudes in the leading-twist accuracy. We find that it is essential to consider the five-quark component and relativistic corrections to evaluate the distribution amplitudes of the nucleon and  $\Delta$  baryon. The results are consistent with the lattice data.

**Plenary Session / 68**

## Compton Scattering on $^4\text{He}$ : Kinematical Features

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In the literature concerning the Generalized Parton (GPDs) distributions of  $^4\text{He}$ , the common opinion is that a single GPD is dominant at high values of the virtuality  $Q$ . Because the Compton form factors (CFFs) are related to the GPDs by sum rules, this implies that a single CFF must be dominant at high  $Q$  and that the data can be safely analyzed in terms of this CFF. In the present study, the phenomenology of deeply virtual Compton scattering (DVCS) is considered. It is a well-known fact that a charged spin zero hadron has five CFFs, all of which contribute to the DVCS amplitude if the absorbed and emitted photons are virtual. This number is reduced to three if the emitted photon is real. [1] The work presented here analyses the behaviour of the CFFs for large  $Q$ . The contributions to the DVCS amplitude of the CFFs that are suppressed by powers of  $Q$  appear to be kinematically enhanced. Moreover, for medium values of  $Q$ , less than the mass of the  $^4\text{He}$  nucleus, for instance attainable at CEBAF, target mass effects are also important.

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B.L.G. Bakker, C.-R. Ji, Few-Body, Syst. 56, 275 (2015)

**Plenary Session / 69**

## Potential Contribution of Korean Groups for the EIC

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The electron ion collider (EIC) is the future particle accelerator to be built at the Brookhaven National Laboratory (BNL). It will collide electrons and various nuclei to precisely measure the internal structure of nuclei, including the spin and momentum distribution of quarks and gluons. It is also expected to provide unprecedented hard probe data to shed light on the strong interaction in medium. The construction of EIC is planned to be done in the early 2030s, and this idea is now materialized by getting the critical decision 1 (CD-1) from the US DOE in July 2021. To participate in this future experiment, 13 faculties from 9 Korean institutions made a consortium and submitted the expression of interest to BNL. In this presentation, we will review the potential contribution of Korean nuclear and particle physics groups in terms of detector R&Ds and physics studies.

**Parallel Session / 70****Single transverse spin asymmetry of the very forward neutral pion production****Author:** Hee-Jin Kim<sup>1</sup>**Co-authors:** Hyun-Chul Kim<sup>1</sup>; Samson Clymton<sup>1</sup><sup>1</sup> *Inha University***Corresponding Author:** heejin.kim@inha.edu

We investigate the single transverse spin asymmetry of the very forward neutral pion production from interferences between  $p$ ,  $\Delta(1232)$ ,  $N^*(1535)$  and  $\Delta(1700)$  Reggeons. The Born amplitudes for the  $p + p^\uparrow \rightarrow \pi^0 + X$  are factorized to the proton-pion-baryon vertex and inclusive proton-baryon amplitude  $A_{pB \rightarrow X}$ . The optical theorem leads these amplitudes to be normalized as differential cross sections for  $pB \rightarrow pB'$  scattering. We will parametrize the cross sections since they are experimentally unknown. The numerical results describe recent experimental data from the RHICf Collaboration very well. The present study indicates that in the low  $p_T$  and large  $x_F$  region  $A_N$  can be understood through Regge-exchange processes.

**Parallel Session / 71****Axial-vector transition form factors from the baryon decuplet to the octet within a pion mean-field approach****Author:** JungMin Suh<sup>1</sup>**Co-authors:** Hyun-Chul Kim<sup>1</sup>; Yuson Jun<sup>1</sup><sup>1</sup> *Inha University***Corresponding Author:** suhjungmin8@gmail.com

In the present talk, we provide the results for the axial-vector transition form factors  $C_5^A(Q^2)$  from the baryon decuplet to the baryon octet, based on a pion mean-field approach, taking into account the rotational  $1/N_c$  corrections and the effects of flavor SU(3) symmetry breaking. We obtain all possible axial-vector transition form factors for both the strange-conserving and strangeness-changing transitions. Since lattice QCD provides only the transition from  $\Delta^+$  to  $p$ , we compare our results for the  $\Delta^+$  to  $p$  transition with those from lattice QCD. For this comparison, we consider the unphysical value of the pion mass corresponding to that lattice calculation have taken. We discuss also the physical implications of the present results.

**Parallel Session / 72****Axial-vector meson  $a_1(1260)$  as a quasi-bound state of the  $K\bar{K}^*$** **Author:** Samson Clymton<sup>1</sup>**Co-author:** Hyun-Chul Kim<sup>1</sup><sup>1</sup> *Inha University*

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In the present talk, we will show how the axial-vector meson  $a_1(1260)$  emerges as a quasi-bound state consisting of the kaon and anti vector kaon or a hadronic molecular state. We first construct a dynamical model for  $\pi\rho$  scattering based on the fully off-mass-shell coupled-channel formalism. The model includes both the  $\pi\rho$  and  $K\bar{K}^*$  channel. The axial-vector meson  $a_1(1260)$  resonance is generated dynamically below the  $K\bar{K}^*$  threshold without any explicit  $a_1$  resonance included. It reveals a certain similarity to the case of scalar meson  $f_0(980)$ , which is well known as the molecular state of the  $K\bar{K}$ . This implies that the  $a_1(1260)$  resonance can be theoretically interpreted as  $K\bar{K}^*$  molecular state or quasi-bound state. We compare the present result to the experimental data on the charge-exchange reaction and finds that it is in good agreement with the mass spectrum corresponding to  $a_1(1260)$ .

**Plenary Session / 73**

## Baryonic form factor of the pion

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Charged pions obviously carry no baryon number. Nevertheless, they possess a nontrivial baryonic structure stemming from isospin breaking by the  $u$  and  $d$  quark mass difference and from the EM effects. We obtain estimates for the pion baryonic form factor in two very different ways: from simple constituent quark models, and from vector meson dominance fits to the experimental  $e^+e^- \rightarrow \pi^+\pi^-$  data. All our estimates consistently yield a positive baryon mean squared radius of  $\pi^+$ ,  $(0.03\text{--}0.04\text{ fm})^2$ . Hence, an intuitive picture emerges where the outer spatial region of  $\pi^+$  has a net baryon density ( $u$  excess), while the inner region a net anti-baryon density ( $d$ -bar excess), both compensating each other such that the total baryon number is zero. For  $\pi^-$  the effect is equal and opposite. We also discuss the challenging lattice prospects of measuring this fundamental property.

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**Parallel Session / 74**

## The pseudoscalar meson dominance and pion-nucleon coupling constant

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Following simple large  $N_c$  arguments and perturbative QCD constraints complemented with uncertainty estimates based on the idea of meson dominance and the half-width rule, we describe the pseudoscalar form factors of the nucleon. We analyze their implications in the space-like region at intermediate and low energies and compare to recent lattice QCD determinations. Our analysis allows for a simple determination of the pion-nucleon coupling constant at a precision level that

matches the most accurate determination to date based on the analysis of the Granada nucleon-nucleon database (8000 experimental  $NN$  scattering data).

**Parallel Session / 75**

## The flavor content of light and heavy-light pseudoscalars mesons

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In the present work, the electroweak properties of light and charmed  $D$  and  $D_s$  pseudoscalar mesons are explored with the covariant constituent quark model. The quark-antiquark-meson vertices are assumed to have a symmetric form by the exchange of quark momenta, which is successful in describing the light pseudoscalar meson properties. The flavor decomposition of the elastic electromagnetic form factors, electromagnetic charge radii, and weak decay constants are calculated. The SU(3) and SU(4) symmetry breaking are discussed, and a comparison with the pion and kaon properties to highlight the Higgs contribution to the structure of these mesons are made. Also, the results are compared with the Lattice.

**Parallel Session / 76**

## Medium modifications of the chiral soliton models

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We discuss in detail the basic ideas behind the medium modifications of the chiral soliton models. We also demonstrate their applications to study an in-medium baryon properties in different (heavy, light) sectors, nuclear matter properties in different (low, ordinary, high, extreme) density regions, the finite nuclei properties and related phenomena.

**Parallel Session / 77**

## Gravitational form factors and pressure distributions for a quark dressed with a gluon

**Authors:** Asmita Mukherjee<sup>None</sup>; JAI MORE<sup>None</sup>; SREERAJ NAIR<sup>None</sup>; Sudeep Saha<sup>1</sup>

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We study the gravitational form factors (GFFs) and the mechanical properties like the pressure and shear distributions inside a relativistic spin- $\frac{1}{2}$  composite object like a quark dressed with a gluon,

using light-front wave functions. Using the symmetric energy-momentum tensor for QCD, we calculate the analytical expression for the four GFFs  $A(q^2)$ ,  $B(q^2)$ ,  $C(q^2)$  and  $\bar{C}(q^2)$  and use them to study the various mechanical properties of the dressed quark state.

**Plenary Session / 78**

## Results from the COMPASS Experiment at CERN

**Author:** Fabienne Kunne<sup>1</sup>

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I will present a selection of results from the COMPASS experiment at CERN. They cover measurements related to the nucleon spin and structure, obtained from deep inelastic scattering (DIS) of muons on longitudinally and transversely polarized nucleons, as well as unpolarized hydrogen. The 3D structure of the nucleon is also studied via exclusive reactions: deep virtual Compton scattering (DVCS) and meson production. Finally, the Drell-Yan process and the J/Psi production are also used to probe the nucleon structure through pion nucleus collisions.

**Plenary Session / 79**

## Advances in Exploration of the Nucleon Resonance Spectrum and Structure

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Studies of the nucleon resonance spectrum and structure offer the unique information on strong interaction dynamics which underlies the generation of excited nucleon states with different structural features. The advances in exploration of the  $N^*$  spectrum which result in discovery of several long time awaited new baryon states (previous “missing resonances”) will be presented. The prospects for extension of the  $N^*$ -spectrum studies from combined analyses of exclusive meson photo-/electroproduction data will be highlighted. The progress in the studies of nucleon resonance electroexcitation amplitudes from exclusive meson electroproduction data with CLAS will be presented. The impact of these results on understanding of emergence of hadron mass achieved within continuum QCD approach will be discussed. Future extension of these efforts in experiments with the CLAS12 detector will be outlined.

**Plenary Session / 80**

## Resonance in Coupled Channel Reactions

**Author:** Toru Sato<sup>1</sup>

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The spectrum and structure of nucleon resonances are investigated analyzing pion, photon and electron induced meson production reactions. The understanding of the GeV lepton induced reaction and of the role of resonances plays important for the long base line neutrino oscillation experiments [1]. In this talk, resonance poles in coupled channel system is discussed [2] using the uniformized Mittag-Leffler expansion developed by Yamada and Morimatsu [3].

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[2] W. A. Yamada, O. Morimatsu, T. Sato and K. Yazaki, arXiv:2018.11605 [hep-ph]

[3] W. Yamada and O. Morimatsu, Phys. Rev. C102, 055201 (2020)

**Parallel Session / 81**

### ***P*-wave bottom baryons of the SU(3) flavor $6_F$**

**Author:** Huimin Yang<sup>1</sup>

<sup>1</sup> *Beihang University*

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We investigate *P*-wave bottom baryons of the  $SU(3)$  flavor  $6_F$ , and systematically study their *D*-wave decays into ground-state bottom baryons and pseudoscalar mesons. A rather complete study is performed on both mass spectra and decay properties of *P*-wave bottom baryons, using the method of QCD sum rules and light-cone sum rules within the framework of heavy quark effective theory. Among all the possibilities, we find four  $\Sigma_b$ , four  $\Xi'_b$ , and six  $\Omega_b$  baryons, with limited widths and so capable of being observed. Their masses, mass splittings within the same multiplets, and decay properties are extracted for future experimental searches.

**Plenary Session / 82**

### **3D Structure of the Nucleon: from JLab12 to JLab24**

**Author:** Harut Avakian<sup>1</sup>

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The quark-gluon dynamics manifests itself in a set of non-perturbative functions describing all possible spin-spin and spin-orbit correlations. Single and Dihadron semi-inclusive and hard exclusive production, both in current and target fragmentation regions, provide a variety of spin and azimuthal angle dependent observables, sensitive to the dynamics of quark-gluon interactions. Studies of transverse momentum distributions of partons are currently driving the upgrades of several existing facilities, and the design and construction of new facilities worldwide. In this talk, we present an overview of the current status and some future measurements of the orbital structure of nucleons at Jefferson Lab.

**Parallel Session / 83**

### **Exploring the Dyson-Schwinger equation in Minkowski space**

**Author:** Dyana Duarte<sup>1</sup>

**Co-authors:** Wayne de Paula <sup>2</sup>; Tobias Frederico <sup>2</sup>; Emanuel Ydrefors <sup>2</sup>

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In recent years, many efforts have been developed to formulate and solve the Bethe-Salpeter and Dyson-Schwinger equations (DSE) directly in Minkowski space, in contrast to the usual procedure of formulation in the Euclidean space and subsequent extension to Minkowski space, which is the approach used in lattice gauge theories. In this work, the fermion self-energy is calculated from the rainbow-ladder truncation of the DSE in quantum electrodynamics (QED) for timelike and spacelike momenta using the Nakanishi integral representation of the fermion propagator. These solutions are in very good agreement with the ones obtained in the Euclidean space in different gauges. We show that this very simple model offers the possibility of the exploration of many different physical problems, such as the chiral symmetry breaking region and could provide a phenomenological model for the pion and its momentum distributions.

**Parallel Session / 84**

## Nucleon electromagnetic properties in a light front quark model

**Authors:** Edson Suisso<sup>1</sup>; Wilson Araujo<sup>2</sup>; João Pacheco De Melo<sup>3</sup>; Kazuo Tsushima<sup>4</sup>; Tobias Frederico<sup>5</sup>

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The nucleon electromagnetic properties are studied in a constituent light front quark model by using a scalar spin coupling between quarks fields and nucleon fields. We have studied a comparison between one scale wave function and two scale wave function. The introduction of a high momentum scale in the wave function moves the value of the square momentum transfer, in which the zero of electric form factor is zero, improving, in the such way, the fit of  $\mu_p G_{Ep}/G_{Mp}$  and also preserving static properties of the nucleon obtained in our previous works, where the wave function used was composed by only one scale.

**Parallel Session / 85**

## Nucleon axial form factor in a light front quark model (canceled)

**Authors:** Edson Suisso<sup>1</sup>; Joao De Melo<sup>2</sup>; Kazuo Tsushima<sup>2</sup>; Tobias Frederico<sup>3</sup>; Wilson Araujo<sup>4</sup>

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In this work we present results on the nucleon axial form factor and on correlations between the static electroweak observables by using a scalar spin coupling between quarks fields and nucleon fields in a constituent light front quark model. In the context of the Bakamjian-Thomas (BT) of the quark spin coupling scheme it was shown that the axial coupling constant, the proton magnetic moment and the radius are correlated by model independent relations. We also have studied a comparison between one scale and two scale wave functions, where the introduction of a high momentum scale in the wave function moves the value of square momentum transfer in which the zero of electric form factor is zero improving in such way that the fit of  $\mu_p G_{E_p}/G_{M_p}$  ratio and also preserving static properties of the nucleon obtained in our previous works, where the wave function used was composed by only one scale.

**McCartor Session / 86**

## Light meson structure on BLFQ

**Authors:** Chandan Mondal<sup>None</sup>; James Vary<sup>1</sup>; Jiangshan Lan<sup>2</sup>; Kay Fu<sup>3</sup>; Xingbo Zhao<sup>None</sup>

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We study the light meson with one dynamical gluon on the light-front quantum chromodynamics (QCD) Hamiltonian as well as a three-dimensional confinement. After fitting the light meson mass spectroscopy, the light-front wave function provides a good description of the pion electromagnetic form factor, decay constant, and the valence quark distribution functions following QCD scale evolution.

**Plenary Session / 87**

## Basis Light Front Quantization - Progress and Prospects

**Author:** James Vary<sup>1</sup>

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Basis Light Front Quantization (BLFQ) has been successfully applied to obtain bound states in both 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. Recent applications include expanding Fock spaces beyond valence fermions to include the dynamical gauge degrees of freedom. I will survey recent applications to QED and to mesons and baryons and discuss prospects for future developments.

**Parallel Session / 88**

## Proton and pion momentum-space 3D structure within basis light-front quantization framework

**Authors:** Zhi Hu<sup>1</sup>; Siqi Xu<sup>2</sup>; Chandan Mondal<sup>None</sup>; Xingbo Zhao<sup>None</sup>; James Vary<sup>3</sup>

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Basis Light-front Quantization is a method starting from the first-principle Lagrangian to simultaneously get the mass spectrum and internal information of many bound states within a feasible computation time. Among the internal information of bound states, transverse-momentum-dependent PDFs (TMDs) have received increasing attention recently because they provide a full momentum space 3D structure of the bound state and are one of the motivations of many planned EIC. In my report, I will first focus on the results of quark TMDs of the proton and pion, both within the BLFQ framework. This shows BLFQ as a very effective and unified framework for investigating the momentum space 3D structure of both spin-zero and spin-half hadrons. Second, I will start with TMDs to investigate single-spin asymmetry (SSA) of some collisions and compare our calculations with some experimental results or model calculations.

**Parallel Session / 89**

## Loop calculations in the null-plane causal perturbation theory

**Authors:** Bruto Pimentel<sup>1</sup>; Oscar Acevedo<sup>1</sup>

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It is well known that light-front field theories suffer from the appearance of higher-order poles when treated in Feynman's approach to perturbative quantum field theory, originated in the non-local terms which arise in Feynman's propagators of some fields in light-front dynamics. The regularization of these terms is a delicate issue, as there are many prescriptions to do it. In null-plane causal perturbation theory, which is a rigorous approach to Heisenberg's S-matrix program in light-front dynamics, on the other hand, Feynman's propagators do not appear in loop calculations, but only the positive- and negative-frequency parts of the commutation distributions of the quantized fields. Consequently, no spurious poles appear in loop distributions, which are ultra-violet finite by construction, allowing to establish the equivalence with instant dynamics in a very clear way. We exemplify loop calculations in the causal approach in Yukawa's model as well as in QED.

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## Parallel Session / 90

**Pion to photon transition form factors with basis light-front quantization**

**Authors:** Chandan Mondal<sup>1</sup>; Sreeraj Nair<sup>None</sup>; Shaoyang Jia<sup>2</sup>; Xingbo Zhao<sup>None</sup>; James Vary<sup>None</sup>

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We obtain the distribution amplitude (DA) of the pion from its light-front wave functions in the basis light-front quantization framework. This light-front wave function of the pion is given by the lowest eigenvector of a light-front effective Hamiltonian consisting a three-dimensional confinement potential and the color singlet Nambu–Jona-Lasinion interaction both between the constituent quark and antiquark. The quantum chromodynamics (QCD) evolution of the DA is subsequently given by the perturbative Efremov-Radyushkin-Brodsky-Lepage evolution equation. Based on this DA, we then evaluate the singly and doubly virtual transition form factors in the space-like region for  $\pi^0 \rightarrow \gamma^* \gamma$  and  $\pi^0 \rightarrow \gamma^* \gamma^*$  processes using the hard-scattering formalism. Our prediction for the pion-photon transition form factor agrees well with data reported by the Belle Collaboration. However, in the large  $Q^2$  region it deviates from the rapid growth reported by the BaBar Collaboration. Meanwhile, our result on the  $\pi^0 \rightarrow \gamma^* \gamma^*$  transition form factor is also consistent with other theoretical approaches and agrees with the scaling behavior predicted by perturbative QCD.

## Parallel Session / 91

**Basis light-front quantization approach to  $\Lambda(\Sigma^0, \Sigma^+, \Sigma^-)$  and  $\Lambda_c(\Sigma_c^+, \Sigma_c^{++}, \Sigma_c^0)$** 

**Authors:** Tiancai Peng<sup>1</sup>; Zhi-Min Zhu<sup>2</sup>; siqi Xu<sup>None</sup>; Jiangshan LAN<sup>3</sup>; Chandan Mondal<sup>None</sup>; Xingbo Zhao<sup>None</sup>; James Vary<sup>None</sup>

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We obtain the masses, the electromagnetic properties, and the parton distribution functions (PDFs) of the baryons (with a strange quark  $\Lambda$  and a charm quark  $\Lambda_c$ , and their isospin triplet baryons) from a light-front effective Hamiltonian in the leading Fock sector. The effective Hamiltonian consists of the confining potential adopted from light-front holography in the transverse direction, a longitudinal confinement, and a one-gluon exchange interaction with fixed coupling. The electromagnetic radii and the magnetic moments are found to be consistent with the available experimental data. We also show a comparison with the other theoretical calculations on the electromagnetic properties of these baryons. We present the gluon and the sea quark PDFs which we generate dynamically from the QCD evolution of the valence quark distributions.

## Parallel Session / 92

**Measurement of transverse single-spin asymmetries of  $\pi^0$  and electromagnetic jets at forward rapidity in 200 and 500 GeV transversely polarized proton-proton collisions at STAR**

**Author:** Zhanwen Zhu<sup>1</sup>

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We present recent results of transverse single-spin asymmetries (TSSAs) for inclusive neutral pions using the Forward Meson Spectrometer at STAR in proton-proton collisions at center of mass energies of 200 and 500 GeV. The results from the two energies show that the pion TSSA increases continuously with Feynman- $x$ . Comparisons with previous measurements show that the pion TSSA is mostly independent of collision energy from 20 GeV to 510 GeV. It is also observed that isolated pions with no other particles nearby tend to have larger TSSA than the non-isolated ones, which may suggest novel mechanisms for generating the TSSA. In order to separate the contributions of initial and final state effects, we also measure the TSSA for the electromagnetic jets and the Collins asymmetry through the TSSA of neutral pions inside the electromagnetic jets. The jet TSSA, sensitive to the initial state effect, follows a similar Feynman- $x$  dependence as the neutral pions, but with a significantly smaller amplitude. The Collins asymmetry, related to the final state effect, shows evidence of a  $j_T$  dependence, which is the pion transverse momentum with respect to the jet axis, and is consistent with zero when integrated over  $j_T$ . These results provide rich information towards understanding the physics mechanism of TSSA in hadron collisions.

**Plenary Session / 93**

## The BGOOD Experiment at ELSA and Multi-Quark Structures in the $uds$ -Sector

**Author:** Hartmut Schmieden<sup>1</sup>

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A leap in our understanding of hadronic structure formation was witnessed during the last decade. The discovery of the  $X, Y, Z$  states in the (hidden) charm meson sector first by Belle, and the  $P_C$  baryon states by LHCb revealed the existence of multi-quark objects beyond the simple quark-antiquark or 3-quark valence configurations. While the detailed structure of such states is still under debate, still the question arises whether similar configurations may exist in the  $uds$ -sector of light quarks as well. I will present ideas on why this may be the case, and first results of the BGOOD experiment at the ELSA electron accelerator of Bonn University on baryonic structures which might be interpreted in support of this.

**Plenary Session / 94**

## Positronium Structure from Light-Front QED Hamiltonian

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The positronium is arguably the simplest bound state in QED. It is often used as a model for studying the structure of hadrons. In this talk, I will report our recent progress in solving the structure of the positronium from the light-front QED Hamiltonian in a basis approach. We include one dynamic photon in the basis. We perform the nonperturbative mass renormalization on the level of the constituent electron and positron. The basis regulators are determined by exploiting the rotational

symmetry of the positronium system. I will compare the obtained low-lying mass spectra with those from nonrelativistic quantum mechanics. Finally, I will present the distribution of the electron and the photon in the positronium in momentum and coordinate space.

**Parallel Session / 95**

## Pion off-shell electromagnetic form factors with the light-front approach models

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The pion plays a special role in the understanding of QCD, the main one is its Goldstone boson nature, associated with the origin of the mass from the dynamical chiral symmetry breaking. One of the possible ways to get information about its substructure, in terms of the degrees of freedom of QCD, quarks and gluons, is from the study of the elastic electron-pion scattering. Because the pion has spin zero, we just need one form factor to describe the matrix element of the current operator between the pion states. However, there is no pion targets and one has to rely on the Sullivan process, where experimental cross-section data from the pion electro-production process on a proton is used to obtain information about the form factor. In the Sullivan process an off-shell pion is picked up from the proton cloud and one has to deal with off-shell effects to extract the form factors and extrapolate it to the on-mass-shell point. In the present work, we explore off-mass-shell effects in the pion electromagnetic form factor by computing it within a light front constituent quarks model, where the Bethe-Salpeter vertex function has a Pauli-Villars form which spreads it with a momentum scale of about a GeV, and compatible with the behavior of the running quark mass in the space-like region obtained from Lattice QCD calculations. We compute the electromagnetic off-shell form factors,  $F_1(q^2, t)$  and  $F_2(q^2, t)$ , the cross-sections for the pion electro-production on the proton and compare it with the available experimental data. This work extends a previous study performed with a covariant model where a point-like pion-quark pseudo-scalar vertex was used to calculate the pion off-shell form factors and the cross-sections.

**Parallel Session / 96**

## Transverse structure of heavy baryons in momentum space: A light-front Hamiltonian approach

**Authors:** Zhi-Min Zhu<sup>1</sup>; Tiancai Peng<sup>2</sup>; Zhi Hu<sup>1</sup>; Siqi Xu<sup>1</sup>; Chandan Mondal<sup>1</sup>; James Vary<sup>3</sup>; Xingbo Zhao<sup>1</sup>

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We investigate the leading-twist transverse-momentum-dependent distribution functions (TMDs) for the  $\Lambda^0$  and the  $\Lambda_c$  heavy baryon, a spin-1/2 composite system consisting of two light quarks ( $u$  and  $d$ ) and a heavy quark  $s/c$ , using the basis light-front quantization (BLFQ) framework. The light-front wave functions of the heavy baryon in the leading Fock sector are obtained from the

eigenfunctions of the light front Schrodinger equation  $\hat{H}_{\text{eff}}|\Psi\rangle = M^2|\Psi\rangle$ , where  $\hat{H}_{\text{eff}}$  is the effective Hamiltonian of the system. We evaluate the TMDs using the overlaps of the light-front wave functions. We also study the spin-densities in momentum space of quarks inside the  $\Lambda^0$  and the  $\Lambda_c$  baryons for various combinations of their polarizations.

**Parallel Session / 97**

## Designing charmonium light-front wavefunctions on a small-basis

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**Co-authors:** Meijian Li<sup>2</sup>; Yang Li<sup>3</sup>; Tuomas Lappi; James Vary

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We present the construction of a simple-functional form light-front wavefunctions (LFWFs) of charmonium states on a small-sized basis function representation. In this work, we modeled the LFWFs for four charmonium states,  $\eta_c$ ,  $J/\psi$ ,  $\psi'$ , and  $\psi(3770)$  as superpositions of orthonormal basis functions. The basis functions are eigenfunctions of an effective Hamiltonian, which has a longitudinal confining potential in addition to the transverse confining potential from light-front holographic QCD. We employ the experimental measurements of charmonium decay widths as well as input from NRQCD to determine the basis function parameters and superposition coefficients. We study the features of those charmonium states using the obtained wavefunctions, including charge radii and parton distribution functions. Additionally, we use the  $J/\psi$  LFWF to calculate the meson production in diffractive deep inelastic scattering and ultra-peripheral heavy-ion collisions, and the  $\eta_c$  LFWF to calculate its diphoton transition form factor. Both results show agreement with experiments.

**Plenary Session / 98**

## Parton Structures in Backward Photo/Electroproduction of Meson

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We construct a Reggeized model for the  $u$ -channel baryon exchange to investigate parton contribution to various types of hadron reactions at backward angles. Backward photoproductions of lighter vector mesons  $\rho^0(770)$ ,  $\omega(785)$ , and  $\phi(1020)$  off the proton target are investigated with a common set of parameters for the parton distribution function. Analysis of pion electroproduction as well as  $\Delta(1232)$  photoproduction in the final state is presented to discuss the parton structure in these reactions. The current model provides a way to observe the respective roles of baryon and partons in the  $u$ -channel exchange process.

**Parallel Session / 99**

## illuminating the nucleon spin (canceled)

**Author:** Miguel Echevarria<sup>1</sup>

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I will discuss the extension of the nucleon spin sum rule to  $QCD \times QED$ . I will present the QED corrections to the evolution of the quark and gluon helicity and orbital-angular-momentum (OAM) distributions, which are calculated for the first time, and the necessary inclusion of photon and lepton helicity and OAM distributions.

**Parallel Session / 100**

## Nucleon structure with dynamic gluon in the light-front frame

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We obtain the light-front wavefunctions (LFWFs) of the nucleon from the light-front quantum chromodynamics (QCD) Hamiltonian, determined for its constituent three-quarks and three-quarks-gluon Fock components, together with a three-dimensional confinement. The eigenvectors of the light-front effective Hamiltonian provide a good quality description of the nucleon electromagnetic and axial form factors, the valence quark distribution functions following QCD scale evolution, and the quark generalized parton distributions functions. We also show various gluon distributions inside the nucleon.

**Parallel Session / 101**

## Generalized parton distributions and spin structures of light mesons from basis light-front quantization

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We present the generalized parton distributions (GPDs) of the pion and the kaon in both momentum and position spaces within the basis light-front quantization framework. We obtain these GPDs for the valence quarks from the eigenvectors of a light-front effective Hamiltonian in the valence Fock sector consisting of the holographic quantum chromodynamics (QCD) confinement potential, a complementary longitudinal confinement potential, and the color-singlet Nambu-Jona-Lasinio interactions. We calculate the generalized form factors of the pion and the kaon from the moments of the GPDs. Combining the tensor form factors with the electromagnetic form factors, we then evaluate the impact parameter dependent probability density of transversely polarized quarks inside the pion and the kaon. The present numerical results for the generalized form factors, and

tensor charges, as well as those for the probability densities and the transverse shift of the polarized densities, are consistent with lattice QCD simulations and the chiral quark models.

**Parallel Session / 102**

## All-charm tetraquark using BLFQ

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We present the first results of all-charm tetraquark calculations using many-body basis function approach in the Front Form of Hamiltonian dynamics known as Basis Light-Front Quantization (BLFQ). We numerically find masses of the ground-state tetraquark and three estimates of the lowest two-meson threshold. All degrees of freedom of each quark and antiquark are explicitly taken into account. We restrict our basis states to overall color-singlet states only. Pauli exclusion principle for identical quarks and identical antiquarks is properly incorporated into the computation. Reconciliation of color-singlets with Pauli exclusion principle requires special attention. We use quadratic confining potential (both transverse and longitudinal) and one-gluon-exchange spin-dependent interactions between particles. We demonstrate that the interactions obey cluster decomposition principle, however, unexpected difficulties force us to make ad hoc modifications to the potentials.

**Parallel Session / 103**

## Singly heavy baryons in nuclear matter from an SU(3) chiral soliton model

**Authors:** Ho-Yeon Won<sup>1</sup>; Ulugbek Yakhshiev<sup>None</sup>; Hyun-Chul Kim<sup>1</sup>

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We discuss how the masses of the singly heavy baryons undergo changes in nuclear matter within the framework of a medium-modified SU(3) chiral soliton model. In order to incorporate a heavy quark inside a singly heavy baryon, we introduce the heavy mesons with heavy-quark spin-flavor symmetry considered. We first reproduce bulk properties of nuclear matter such as the saturation energy and pressure by fitting the model parameters in the light-quark sector. Using the bound-state approach, we produce the states of the singly heavy baryons by combining the SU(3) chiral soliton with the heavy mesons. They emerge as the states with the right hypercharge  $Y_R = 2/3$  that picks up the baryon antitriplet ( $\bar{3}$ ) and the sextet (6) properly. We then associate with the medium effects on the heavy mesons, which are essential in determining the mass dropping or raising of the singly heavy baryons. We find that information on the change of the heavy meson masses in nuclear medium is crucial in explaining the behavior of the masses of the singly heavy baryons.

**Parallel Session / 104**

## Pair production in strong inhomogeneous electric fields

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We investigate the electron-positron pair production in electric fields with spatio-temporal inhomogeneity using a Hamiltonian method based on light-front quantization. We truncate the Fock space up to the sector containing 4 pairs of electrons and positrons, by which we can track each particle fully quantum-mechanically. We calculate observables such as the invariant mass and the longitudinal momentum distribution of the produced pairs as a function of evolution time. We observe a critical intensity of background field, above which the pair production rate is no longer oscillating with time periodically as in perturbation theory. This work may provide the foundation for the study of the pair production process in strong fields with realistic spacetime structures.

**Parallel Session / 105**

## The axial-vector transitions between the singly charmed baryons within a mean-field approach

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**Co-authors:** JungMin Suh<sup>1</sup>; Hyun-Chul Kim<sup>1</sup>

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A chiral quark-soliton model (CQSM) is a relativistic pion mean-field approach in the large  $N_c$  limit, which describes baryon as a bound state of the  $N_c$  valence quarks by the pion mean field. In the infinitely heavy mass limit of the heavy quark, a singly heavy baryon can be viewed as an  $N_c - 1$  chiral soliton with the heavy quark as a static color source. In this framework, we evaluate the axial-vector transition form factors of the low-lying singly charmed baryons. The  $1/N_c$  rotational corrections and the effects of flavor SU(3) symmetry breaking were taken into account. We investigate the contributions from the valence and sea quarks to the axial-vector transition form factors and, the valence-quark contributions are dominant in all transition processes. Moreover, we find that the effects of flavor SU(3) symmetry breaking are marginal in general.

**Parallel Session / 106**

## Charmonium spectrum from the instanton liquid model

**Authors:** Hyun-Chul Kim<sup>1</sup>; Kihoon Hong<sup>1</sup>; Mirzayousuf Musakhanov<sup>2</sup>; Nurmukhammad Rakhimov<sup>2</sup>; Ulugbek Yakhshiev<sup>None</sup>

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The structure of charmonia is usually described by two important physics: Coulomb-like potential arising from one-gluon exchange and quark-confining one to keep the quarks inside charmonia. However, the strength of the strong coupling constant often employed in this potential approach is known to be overestimated. While the effects from the instanton, which is one of the most well-known nonperturbative object in QCD, are of great importance to describe light hadrons, they are suppressed in the heavy-quark sector. Nevertheless, the heavy-quark potential derived from the instanton vacuum provides certain contribution to the masses of charmonia such that almost the physical value of the strong coupling constant can be used. In the present talk, we present recent

studies on the instanton effects on the charmonia. These effects influence also the Coulomb-like interaction from one-gluon exchange. Combining the existing terms in the heavy-quark potential with those from the instanton vacuum, We obtain the mass spectrum of the charmonia. We also present the results for the  $E1$  and  $M1$  radiative transitions.

**Parallel Session / 107**

## Light front approach to hadrons on quantum computers

**Author:** Wenyang Qian<sup>1</sup>

**Co-authors:** Robert Basili<sup>1</sup>; Soham Pal<sup>1</sup>; Glenn Luecke<sup>1</sup>; James Vary<sup>1</sup>

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Following our previous work (W. Qian, S. Jia, Y. Li and J.P. Vary, Phys. Rev. C 102, 055207 (2020); arXiv:2005.13806) on light unflavored mesons as a relativistic bound-state problem within the non-perturbative Hamiltonian formalism, we present the numerical calculations on simulated quantum devices using the basis light-front quantization (BLFQ) approach. We implement and compare the variational quantum eigensolver (VQE) and the subspace-search variational quantum eigensolver (SSVQE) to find the low-lying mass spectrum of the light meson system and its corresponding light-front wave functions (LFWFs) via quantum simulations. Based on these LFWFs, we then evaluate the meson decay constants and parton distribution functions. Our quantum simulations are in reasonable agreement with the exact classical solution.

**Parallel Session / 108**

## Pion and kaon valence and gluon distribution functions

**Author:** Parada Hutaauruk<sup>1</sup>

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In this talk we study the valence quark and gluon distributions of the pion and kaon in the Nambu-Jona-Lasinio (NJL) model with the help of the proper-time regularization (PTR) scheme that simulates confinement. We then explore the gluon contents of the pion and kaon, that recently attract more attention of hadronic physicist. A comparison with other model and lattice predictions as well as the change of the gluon distribution in medium will be presented and discussed.

**Parallel Session / 109**

## Light-front transverse momentum distributions for $J = 1/2$ hadronic systems in valence approximation

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The semi-inclusive correlator for a  $J = 1/2$  bound-system, composed by  $A$  spin- $1/2$  fermions, is linearly expressed in terms of the light-front Poincare' covariant spin-dependent spectral function, in valence approximation. The light-front spin-dependent spectral function is fully determined by six scalar functions that allow for a complete description of the six T-even transverse-momentum distributions, suitable for a detailed investigation of the dynamics inside the bound system. The application of the developed formalism to a case with a sophisticated dynamical content, like  ${}^3\text{He}$ , reaches two goals: (i) to illustrate a prototype of an investigation path for gathering a rich wealth of information on the dynamics and also finding valuable constraints to be exploited from the phenomenological standpoint; (ii) to support for the three-nucleon system a dedicated experimental effort for obtaining a detailed 3D picture in momentum space. In particular, the orbital-angular momentum decomposition of the bound state can be studied through the assessment of relations among the transverse-momentum distributions, as well as the relevance of the relativistic effect generated by the implementation of macrocausality. A fresh evaluation of the longitudinal and transverse polarizations of the neutron and proton is also provided, confirming essentially the values used in the standard procedure for extracting the neutron structure functions from both deep- inelastic scattering and semi-inclusive reactions, in the same kinematical regime.

**Parallel Session / 110**

## Relations between generalized parton distributions and transverse momentum dependent parton distributions

**Author:** Bheemsehan Gurjar<sup>1</sup>

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In this talk, I would like to present some trivial and non-trivial relations between transverse momentum-dependent parton distributions (TMDs) and generalized parton distributions (GPDs) in a light-front quark-diquark model motivated by soft-wall AdS/QCD. And I will show that the relation between the Sivers function and GPD  $E^q$  can be obtained in terms of the Lensing function and I will compare our LFQDQ model relations with different models. And if time permits then I'll also discuss the decomposition of the quark Orbital Angular Momentum. And I'll show the results for the kinetic and canonical OAM for the quarks.

**Parallel Session / 111**

## LCSR application to $p \rightarrow e^+ \gamma$ decay

**Authors:** Anshika Bansal<sup>1</sup>; Namit Mahajan<sup>2</sup>

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The proton decay is forbidden in the standard model of particle physics. Hence, any signature of proton decay will be a clear signal of new physics beyond the standard model. In this talk, we discuss the  $p \rightarrow e^+\gamma$  decay. It is mediated by the baryon number violating operators of dimension 6 and includes two form factors. We discuss these form factors in the framework of light cone sum rules and present the numerical estimates of the branching ratio for the decay.

**Plenary Session / 112**

## **From Instant to Light-Front: Opening LC2021**

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Since Dirac proposed the light-front form of the relativistic dynamics in 1949, the ILCAC put together a white paper entitled “Light-front Quantum Chromodynamics” (LFQCD) as a framework for the analysis of hadron physics in 2013. Its goal was to find solutions that describe hadrons in the theory of strong interactions, QCD. Many progresses have been made toward the specific goals of this approach since then. Opening LC2021, I will present an effort to link between the instant form dynamics that makes a close contact with the Euclidean space approach and the light-front dynamics that works strictly in the Minkowski space. Recent developments in QED<sub>3+1</sub> and QCD<sub>1+1</sub> at  $N_c \rightarrow \infty$  will be discussed.

**Plenary Session / 113**

## **Canonical Approach for Extreme QCD**

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<sup>1</sup> *Pukyong National University*

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In this talk, we present our recent work for a canonical approach for extreme QCD. We discuss the canonical approach for the study of QCD phase at finite densities and temperatures in the confinement phase. The canonical approach, which is a method to extrapolate observables calculated at pure imaginary chemical potentials to those at real chemical potentials, is useful to overcome the sign problem in lattice QCD simulations at finite density. To validate the applicability of the approach, we employ the Nambu-Jona-Lasinio (NJL) and Polyakov-NJL (PNJL) models where exact solutions for the number density are available, which is the basic input of the fugacity expansion and can be compared with those of the canonical approach. We find that the number densities computed from the canonical approach are consistent with the exact solutions in most of the confinement phases. The results in the present study are applicable to the study of lattice QCD.

**Plenary Session / 114**

## **Recent Results on Baryon Structures and Dark Sector Searches at Belle and Belle II**

**Author:** Youngjoon Kwon<sup>1</sup>

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The Belle experiment using KEKB collider at KEK, Japan, has made immense contribution to heavy flavor physics with observations of CP violation in B systems and rare B-meson decay measurements. The Belle II experiment using SuperKEKB is an upgrade of Belle and aims at collecting 50 times more data. In this talk, we present a selection of recent physics results from Belle. In particular, we will discuss recent results in the baryon spectroscopy and structures from Belle as well as searches for dark sector phenomena from Belle and Belle II.

**Plenary Session / 115**

## **Pseudodistributions: PDFs Off the Light Cone**

**Author:** Anatoly Radyushkin<sup>1</sup>

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I formulate the basic concepts underlying the development of parton pseudodistributions functions and review its recent applications to the lattice QCD extractions of parton distributions.

**Plenary Session / 116**

## **Origins of the Proton Mass**

**Author:** Ian Cloet<sup>1</sup>

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The proton, and its isospin partner the neutron, are the building blocks of the visible universe and are responsible for almost the entirety of its mass. While the total mass of the proton is precisely known, the decomposition of this mass into its quark and gluon components touches upon some of the deepest mysteries in QCD. This talk will review this topic, discuss some of the recent theory progress, and explore possibilities for experiment.

**Plenary Session / 117**

## **The SoLID Science Program in Hall A at Jefferson Lab**

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The science program enabled by the Solenoidal Large Detector Device (SoLID) in Hall A at Jefferson Lab encompasses studies of nucleon structure addressing some of the fundamental questions in hadron structure. It will explore the nucleon origins of mass and spin in the framework of Quantum

Chromodynamics at the luminosity frontier. It will also seek signatures of physics beyond the standard model of particle physics in the electroweak sector. I will discuss the SoLID science program and its impact on our knowledge of nucleon structure in the valence quark region for both quarks and gluons. SoLID has undergone a successful DoE science review, and the collaboration is eager to hear news on a DOE critical decision zero (CD0) soon.

**Plenary Session / 118**

## Recent Progress of Hypernuclear Physics

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In hypernuclear physics, during two decade, we have been obtaining many epoch-making data which are related to information on hyperon-nucleon and hyperon-hyperon interactions. In this talk, I will introduce the recent progress and future prospect at J-PARC in hypernuclear physics from theory side.

**Plenary Session / 119**

## Light-Front Quantization as an Effective Field Theory

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Light-front quantization focuses on a particular type of modes in full QCD, the soft and collinear modes in a pre-selected direction, which are useful to describe the quark and gluon structure of the hadrons traveling at the speed of light in the direction. The standard approach to obtain the Hamiltonian and Feynman rule is to take the infinite momentum limit before imposing a UV cut-off, a methodology adopted frequently in effective field theories. This arrives at the beautiful and simple language of partons but generates considerable difficulty in renormalization of the theory, which mixes both IR and UV physics. Large-momentum effective theory may provide an alternative to light-front quantization which keeps the feature but fixes the difficult.

**Plenary Session / 120**

## Confinement in Two-Dimensional QCD and the Infinitely Long Pion

**Author:** Gerald Miller<sup>1</sup>

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Three current models of QCD in (1+1) dimensions are examined and extended in light-front coordinates. A pion of high momentum is found to have an infinite extent along its direction of motion.

**Plenary Session / 121**

## Going to the Light Front with Contour Deformations

**Author:** Gernot Eichmann<sup>1</sup>

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In this talk I present a new method to compute the light-front wave functions for a system of two interacting scalar particles using contour deformations. After solving the two-body Bethe-Salpeter equation, the projection onto the light front is done through a combination of contour deformations and analytic continuation methods. The resulting light-front wave functions and distribution amplitudes are in agreement with the Nakanishi method frequently used in the literature. Finally, several extensions of the model towards unequal-mass systems and complex conjugate propagator poles are studied to make contact with QCD.

**McCartor Session / 122**

## McCartor Fellowship Ceremony

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**Plenary Session / 123**

## A New Class of Exclusive Processes to Better Measure the $x$ -Dependence of DAs and GPDs

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We propose a new class of exclusive processes for extracting generalized parton distribution functions (GPDs), which provide a powerful theoretical tool to quantify the spatial distribution of quarks and gluons inside a bound hadron. Using exclusive massive-photon-pair production in meson-meson and meson-baryon collisions as an example, we show that the leading non-perturbative contribution to these processes are universal and can be factorized into pion DAs and hadron GPDs, and this class of processes can be systematically studied in terms of QCD factorization approach. We demonstrate quantitatively that these processes offer an enhanced sensitivity to the momentum fraction  $x$  of DAs and GPDs, and they are measurable at various facilities worldwide.

**Plenary Session / 124**

## Foundations of the Parton Model Description of TMDs

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Feynman's parton model played an important role for the understanding of the Bjorken scaling in the first DIS experiments and paved the way towards QCD. Various versions of parton model frameworks have been used in literature to study nucleon structure, target mass corrections and other partonic properties. The properties of the quark correlator are determined by the equations of motion of the free partons. This has recently been explored by two different groups leading to different results regarding the number of independent structures in the description of transverse momentum dependent parton distribution functions (TMDs). In this work, we systematically investigate the foundations of the parton model description of TMDs, and explain the discrepancies between the different results in literature.

Plenary Session / 125

## Spectroscopic Study of Quark Dynamics in Baryons at J-PARC

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Hadrons are complex systems of quarks (and gluons) first formed and followed by matter evolution in the universe. The strong interaction plays an important role in formation of matter. The quantum chromodynamics (QCD), which is the fundamental theory of the strong interaction, shows highly non-perturbative behaviors in low energy and thus is difficult to solve. A fundamental question, how hadrons are built from quarks, has not yet been answered clearly.

The most important behavior in low energy QCD is a spontaneous breaking of chiral symmetry caused by non-trivial QCD vacuum. As a result, constituent quarks with earning a finite mass due to chiral condensate emerge. At the same time, Nambu-Goldstone bosons, such as pions, are generated. Features of hadrons, are thus to be described by the dynamics of constituent quarks. Confinement force, one-gluon-exchange, and instanton-induced interactions are often employed as effective interactions between constituent quarks. By these, the level structure depending on internal motions and spins of quarks in hadrons are characterized. Production cross sections and/or decay total/partial width (decay branching ratios) are also responding to internal structure of hadrons.

Systematic studies of excited baryons with heavier flavors such as strange and charm quarks provides good opportunities to investigate the dynamics of the constituent quarks as internal quark motions can be disentangled by introducing different flavors in baryons. Quark-quark (diquark) correlations appearing in excited states are of particular interest. They are related to the spin-dependent interactions originated in the non-trivial QCD vacuum.

At the J-PARC Hadron Experimental Facility, we will be able to study excited singly-charmed ( $\Lambda_c/\Sigma_c$ ) and doubly/triply-strange ( $\Xi/\Omega$ ) baryons by utilizing intense pion and kaon beams up to 20 GeV/c. By means of missing mass techniques, we will measure those baryons up to highly excited states inclusively. Through systematic measurements of their masses, spin-parities, production rates, and decay branching ratios, we will reveal the diquark correlations and the origin of the spin-dependent interaction behind them.

Plenary Session / 126



## Highlights from ATLAS and Future Plans

**Author:** Massimo Corradi<sup>1</sup>

**Co-author:** Sandra Leone<sup>2</sup>

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An overview of the ATLAS physics program is presented, with emphasis on the most recent results obtained fully exploiting the abundant and now well-understood dataset recorded during Run 2 of CERN's Large Hadron Collider (2015-2018). The talk will also describe the ongoing improvements of the ATLAS detector targeting Run 3 and the subsequent LHC high luminosity phase.

Plenary Session / 127

## Nucleon Parton Distributions from Lattice QCD

**Author:** Jiunn-Wei Chen<sup>1</sup>

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I will update the progress on the determination of nucleon parton distributions on the lattice using the large momentum effective field theory approach.

Plenary Session / 128

## Deeply Virtual Compton Scattering on the Neutron with CLAS12 at Jefferson Lab

**Author:** Silvia Niccolai<sup>1</sup>

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A key step to improve our understanding of nucleon structure in terms of Generalized Parton Distributions (GPDs) is the measurement of Deeply Virtual Compton Scattering on the neutron (nDVCS;  $ed \rightarrow e'n(p)$ ). This process provides mainly, in the kinematic range covered at Jefferson Lab, an access to the GPD  $E$  of the neutron, which is the least known and constrained GPD as of today. The measurement of  $E$ , together with  $H$ , yields information on the quark total angular momentum –via the Ji's sum rule –the missing ingredient to understand the nucleon spin composition. The GPD  $E$  is accessed in nDVCS by measuring the Beam Spin Asymmetry (BSA). The measurement of the BSA of nDVCS, combined with other nDVCS observables and from those obtained in pDVCS measurements, will allow to perform the quark-flavor separation of the GPDs. This talk will report on the experiment recently carried out at Jefferson Lab with a 10.5-GeV polarized electron beam, the Hall-B CLAS12 detector, and a liquid deuterium target. Details on the data analysis along with preliminary beam-spin asymmetries for nDVCS will be presented. An overview of the imminent experiment on nDVCS with CLAS12 and a longitudinally polarized target will also be provided.

**Plenary Session / 129**

## Challenges and Opportunities in Hadron Physics

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Newly operational, anticipated, and planned facilities have the potential to change the hadron physics landscape. Each one of the participants has expressed their perspective on how our community can advance over this new ground. This presentation will attempt to capture some of the excitement surrounding the journeys that are underway or may soon begin.

**Plenary Session / 130**

## Status and Prospects of the Electron Ion Collider

**Author:** Abhay Deshpande<sup>1</sup>

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In January 2020, the US DOE approved the realization of the Electron Ion Collider (EIC) to be built at Brookhaven National Laboratory (BNL) in partnership with Jefferson Laboratory. An “EIC project” was stood up and it is now leading the realization of the machine and working with the world-wide EIC Users towards the construction of up to two EIC detectors. In this talk, I will review the science of EIC and then present the current status of the EIC and detector planning including the state of physics collaborations and detector designs.

**Plenary Session / 131**

## FAIR Physics with PANDA

**Author:** Kai-Thomas Brinkmann<sup>1</sup>

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The Facility for Antiproton and Ion Research, FAIR, is under construction near Darmstadt, Germany. Among other large-scale installations, the PANDA (Antiproton annihilations in Darmstadt) experiment is designed to answer pressing questions in the charmonium mass region. At PANDA, an antiproton beam with momenta up to 15 GeV/c circulating in the high-energy storage ring HESR will interact with a hydrogen target. High interaction rates and unprecedented momentum precision will allow experiments addressing, among a variety of other physics goals, hidden and open charm spectroscopy. The detector system of PANDA is optimized to meet the challenges of high-resolution spectroscopy of charmonium states of any quantum number in formation and production with very good background suppression. At the same time, emphasis is placed on meeting the requirements of other parts of the physics program as, e.g. hyperon spectroscopy. The design of the subsystems of the PANDA spectrometers, a target solenoid and forward dipole, is well advanced. Prototypes

have been subjected to beam tests, components are being prepared for early physics experiments. A status report on the detector components will be given and the physics reach of the full detector assembly will be underlined with studies in selected benchmark channels. Progress towards the realization of PANDA will be discussed alongside aspects of the physics program with emphasis on charm in baryons and mesons.

Work supported by BMBF and HFHF. PANDA is supported by the national funding agencies of the participating groups.

**Plenary Session / 132**

## **Mechanical Properties of the Proton**

**Author:** Volker Burkert<sup>1</sup>

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**Plenary Session / 133**

## **Hadron Physics with AMBER at CERN**

**Author:** Jan Friedrich<sup>1</sup>

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NA66/AMBER (Apparatus for Meson and Baryon Experimental Research) has been approved at the CERN Super Proton Synchrotron for a broad research program in quantum chromodynamics. The program ranges in a first phase to about the year 2026, from a precision measurement of the proton radius using a 100-GeV muon beam, to investigations of the quark-gluon structure of mesons in Drell-Yan processes. The program for the second phase is foreseen to be focused on employing radio-frequency separated kaon beams that will allow to extend the investigations to the strangeness sector.

**Plenary Session / 134**

## **Higher-Spin Baryon Photoproduction with Twisted Photons**

**Author:** Carl Carlson<sup>1</sup>

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We may anticipate that future accelerator facilities will include the possibility of energetic twisted photons, which are photons with a structured wave front that can allow a pre-defined large angular momentum along the beam direction. Twisted photons are potentially a new tool in hadronic physics, and we consider here the possibility of selective photoproduction of higher-spin baryons using twisted photons. We show that particular polarization amplitudes can isolate higher-spin partial wave amplitudes, and selectively enhance signals from high spin baryons with minimal interference from lower spin resonances that are otherwise dominant.

**Plenary Session / 135**

## **Novel Properties of Hadron Physics Derived from Holographic Light-Front QCD**

**Author:** Stanley Brodsky<sup>1</sup>

<sup>1</sup> *SLAC National Accelerator Laboratory*

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I will discuss some new developments in hadron physics which can be derived from light-front holography and superconformal quantum mechanics. This includes new insights into the physics of color confinement, chiral symmetry, the spectroscopy and dynamics of hadrons, as well as surprising supersymmetric relations between the masses and light-front wavefunctions of mesons, baryons, and tetraquarks. I will also discuss some novel features of QCD in hadron physics, including color transparency, and asymmetric intrinsic heavy-quark phenomena.

**Plenary Session / 136**

## **Welcome Address**

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**Plenary Session / 138**

## **Zero Modes and the Vacuum**

**Author:** Matthias Burkardt<sup>1</sup>

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I will discuss how a trivial light cone vacuum can be compatible with a nontrivial vacuum in an equal time framework. In particular I will discuss the role of zero modes and their role in the light-front formulation.

**Plenary Session / 139**

## **Future Opportunities with CEBAF Upgrades**

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**Plenary Session / 140**

## **Current Highlights and Future Prospects from CMS**

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Since 2010, the Compact Muon Solenoid (CMS) Experiment at the CERN Large Hadron Collider (LHC) has collected an unprecedented amount of proton-proton collision data in the center of mass energies of 7, 8 and 13 TeV. These data are used to conduct hundreds of analyses that test the validity of the standard model and look for hints of beyond the standard model physics. The biggest highlight so far has been the discovery of the Higgs boson. The quest continues via a large diversity of measurements and searches aiming to explore all theoretical possibilities. Moreover, the upcoming technical upgrades for the high-luminosity LHC (HL-LHC) and the Phase2 detectors promise a further wealth of physics prospects. This talk will present various recent physics results obtained with the CMS Run2 data and overview prospects for the future HL-LHC program.