LC2019 - QCD on the light cone: from hadrons to heavy ions

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Book of Abstracts

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Ward-Takahashi Identity in QED_4 at One-loop Level in the Light-front Gauge

Authors: Chueng-Ryong Ji[1]; Alfredo T. Suzuki[2]

[1] *North Carolina State University*

[2] *La Sierra University*

Corresponding Authors: asuzuki@lasierra.edu, crji@ncsu.edu

The Ward-Takahashi identity in quantum electrodynamics (QED_4) first considered by J. C. Ward and Y. Takahashi, correlates the wave function renormalization for the electron to its vertex renormalization function, guaranteeing the cancellation of ultraviolet (UV) divergences to all orders of perturbation theory.
Since QED in the light-cone gauge is a constrained theory that brings a more demanding UV renormalization program due to the inevitable non-local terms, we check the Ward-Takahashi identity to the one-loop level, using the Mandelstam-Leibbrandt prescription to handle the characteristic light-cone poles that appear in the Feynman integrals.

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Impact parameter dependence of collinearly improved Balitsky-Kovchegov evolution

Author: Marek Matas[None]

Corresponding Author: matas.marek1@gmail.com

The Balistky-Kovchegov equation has been solved including the impact-parameter dependence. Previous attempts to include this dependence have been spoiled by the presence of the so-called Coulomb tails produced by the evolution. We show, that using the collinearly-improved kernel to the BK equation, the Coulomb tails are heavily suppressed which allows for a correct description of existing data –both of the structure function and exclusive vector meson production–, as well as for the prediction of processes that are feasible for measurement at future facilities such as EICs.

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The DVCS experiment in Hall C at Jefferson Lab with the new NPS detector

Author: Ho San KO[1]

Co-author: Carlos Munoz Camacho

[1] *Paris-Sud University*

Corresponding Authors: munoz@jlab.org, ho-san.ko@u-psud.fr

Deeply Virtual Compton Scattering (DVCS) is the simplest exclusive process to access Generalized Parton Distributions (GPDs). GPDs encode the correlation between the spacial distribution of partons inside the nucleon and their momentum. An upcoming DVCS experiment in Hall C at Jefferson Lab (Virginia, U.S.A.) will provide the highest precision data in a vast Q^2- x_B region accessible by a 11 GeV electron beam. It will further test the leading twist dominance of the observables and get

more precise data in lower x_B region needed for the full mapping of GPDs. A Neutral Particle Spectrometer (NPS) is being developed for this experiment. It consists of an electromagnetic calorimeter made of 1080 $PbWO_4$ crystals. We will present the status of the detector R&D and construction, as well as simulation results of its performance.

Parallel 3 / 5

Partonic orbital angular momentum in the nucleon's chiral periphery

Authors: Carlos Granados[None]; Christian Weiss[1]

[1] *Jefferson Lab*

Corresponding Authors: weiss@jlab.org, carlosg@jlab.org

The transverse spatial distribution of orbital angular momentum (OAM) in the nucleon is studied at peripheral distances b~1/Mπ. We use Chiral EFT to compute the form factors of the energy-momentum tensor and their peripheral transverse densities, including the density associated with light-front OAM. This density is represented in first–quantized form, as an overlap integral of chiral light–front wave functions describing the transition of the nucleon to soft pion–nucleon intermediate states. We identify the operator generating the OAM density in transverse coordinate space and show that it has the form of the mechanical OAM of the peripheral pion, which permits a simple physical interpretation of peripheral OAM. We extend the approach to include Delta isobar intermediate states and demonstrate the large-N_c relations for the OAM density.

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Pion observables with the Minkowski Space Pion Model

Authors: João P. De Melo[1]; Tobias Frederico[2]; Rômulo Moita[3]

[1] *Universidade Cruzeiro do Sul*

[2] *Instituto Tecnologico de Aeronautica*

[3] *ITA - CTA*

Corresponding Authors: tobias@ita.br, jpachecodm@gmail.com

The pion structure in Minkowski space is described in terms of an analytic model of the Bethe–Salpeter amplitude combined with Euclidean Lattice QCD results [1,2]. The model is physically motivated to take into account the running quark mass, which is fitted to Lattice QCD data [3]. In the present work, we extend the previus work donne in [2], with the present model utilized to calculated the pion observables, in order to test the parameters dependence and the consequences for the pion observables, and, see the limits of the model presented in terms of the initial parameters. The model is build in order to fit quark propagator in the space-like region, from the lattice calculations with the Landau gauge [3]; that choice preserve the Lorentz invariance of the QCD. The Lattice calculation utilized here, have two degenerate light quarks, u and d, and, also the heavy s quark. The pion pseudoscalar vertex is associated to the quark mass function, as dictated by dynamical chiral symmetry breaking requirements in the limit of vanishing current quark mass. The quark propagator is analyzed in terms of a spectral representation, and it shows a violation of the positivity constraints. The pion Bethe–Salpeter amplitude is also built in terms of a integral presentation. The pion space-like electromagnetic form factor is calculated with a quark electromagnetic current, which satisfies the Ward–Takahashi identity to ensure current conservation. The results for the form factor and weak decay onstant are found to be consistent with the experimental data [4-8].

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Parallel 1 / 9

A proton imaging via double parton scattering

Authors: Matteo Rinaldi[1]; Federico Alberto Ceccopieri[2]; Sergio Scopetta[None]; Marco Traini[3]; Vicente Vento Torres[4]

[1] *Dipartimento di Fisica e Geologia. Università degli studi di Perugia. INFN section of Perugia.*

[2] *Universita & INFN, Milano-Bicocca (IT)*

[3] *INFN - TIFPA, Dipartimento di Fisica, Università degli Studi di Trento, Via Sommarive 14, I-38123 Povo, Trento, Italy*

[4] *Univ. of Valencia and CSIC (ES)*

Corresponding Authors: matteo.rinaldi@pg.infn.it, marcoclaudio.traini@unitn.it, vicente.vento@uv.es, sergio.scopetta@pg.infn.it, federico.alberto.ceccopieri@cern.ch

Here we discuss the main outcomes of our investigations on the so called double parton distribution functions (dPDFs). These quantities can be obtained via double parton scattering processes (DPS) in high energy proton-proton and proton nucleus collisions. These new and experimentally unknown distributions represent a novel and promising complementary tool, w.r.t. TMDs and GPDs, to access the 3D partonic structure of the proton. In particular, dPDFs encode new information on two parton correlations in hadrons which cannot be accessed through, e.g., GPDs. In our studies, model calculations have been used to investigate how double correlations affect dPDFs. We considered a fully relativist treatment by using the the Light-Front approach [1]. In this framework, we showed how dynamical correlations, induced by the used model, prevent the factorization of dPDFs in terms of standard PDFs, a common assumption in experimental analyses. Furthermore, since for the moment being dPDFs cannot be directly observed, we also discuss how correlations affect an essential ingredient for the comprehension of the role of DPS in proton-proton collisions used in experimental studies, the so called effective cross section, σ_{eff}. To this aim, dPDFs have been evolved at the experimental momentum scales through the pQCD evolution procedure and then used to calculate σ_{eff}. We claim that the x dependence of σ_{eff}, being x the longitudinal momentum fraction carried by a parton inside the hadron, represents the cleanest evidence of partonic correlations [2]. We have also calculated the DPS cross section for the same sign W pair production process using, as non perturbative input, dPDFs evaluated within a constituent quark model. We showed that partonic correlations could be observed in next LHC run [3]. Furthermore, since indications on the magnitudo of σ_{eff} are available, we also demonstrated how the mean value of σ_{eff} can be related to the mean parotinc distance between two parton active in a DPS process [4].
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Parallel 2 / 10

Forward jet cross sections: from trijet to NLO dijet

Authors: Yair Mulian[None]; Edmond Iancu[1]

[1] *Université Paris-Saclay (FR)*

Corresponding Authors: yair25m@gmail.com, edmond.iancu@cea.fr

Using the formalism of the light-cone wave function in pQCD together with the hybrid factorization, we compute the cross-section for two and three particle production at forward rapidities in proton-nucleus collisions. We focus on the quark channel, in which the three produced partons – a quark accompanied by a gluon pair, or two quarks plus one antiquark – are all generated via two successive splittings starting with a quark that was originally collinear with the proton. The produced partons are put on-shell by their scattering off the nuclear target, described as a Lorentz-contracted "shock-wave". By using the three-parton component of the quark light-cone wave function, together with the virtual corrections, we can then present our progress on the computation of the next-to-leading order correction to the cross-section for the production of a pair of jets.

Parallel 2 / 11

Study of twist-2 distribution amplitudes and the decay constants of pseudoscalar and vector heavy mesons in light-front quark model

Authors: Nisha Dhiman[1]; Harleen Dahiya[2]; Chueng-Ryong Ji[3]; Ho-Meoyng Choi[4]

[1] *Dr. B. R. Ambedkar National Institute of Technology Jalandhar*

[2] *Dr. B.R. Ambedkar National Institute of Technology*

[3] *North Carolina State University*

[4] *Kyungpook National University*

Corresponding Authors: nishdhiman1292@gmail.com, homyoung@knu.ac.kr, crji@ncsu.edu, dahiyah@nitj.ac.in

We study the twist-2 distribution amplitudes (DAs) and the decay constants of pseudoscalar as well as the longitudinally and transversely polarized vector heavy (D, D_s, B and B_s) mesons in the light-front quark model with the Coulomb plus exponential-type confining potential $V_{\rm exp} = a + be^{\alpha r}$ in addition to the hyperfine interaction. We first compute the mass spectra of ground state pseudoscalar and vector heavy mesons and fix the model parameters necessary for the analysis, applying the variational principle with the trial wave function up to the first three lowest order harmonic oscillator (HO) wave functions $\Phi(x, \mathbf{k}_\perp) = \sum_{n=1}^{3} c_n \phi_{nS}$. We then obtain the numerical results for the corresponding decay constants. We analyze the variation of DAs as a function of momentum fraction. We also compare our results with the available experimental data as well as with the other theoretical model predictions.

Parallel 2 / 12

Investigating transverse momentum distributions with jets

Author: Daniel G. Reyes[1]

[1] *Complutense University of Madrid*

Corresponding Author: dangut01@ucm.es

In this talk we investigate the use of jets to measure transverse momentum distributions. We study the effect of the election of the axis in the description of the jet. Critically, for an axis insensitive to recoil, the so called Winner-Take-All axis, the jet TMD has the same double-scale renormalization group evolution as TMD fragmentation functions for all radii R. This fact means that TMD fragmentation functions that appear in factorization theorems for processes with hadrons in the final state may then simply be replaced by the jet TMDs we calculate, and all ingredients to perform the resummation to next-to-next-to-next-to-leading logarithmic accuracy are available. Some numerical results for interesting cases as dijet momentum decorrelation and (un)polarized semi-inclusive deep inelastic scattering (SIDIS) with a jet in the final state are studied and presented. This last case allows to find a clean method to probe the intrinsic transverse momentum of quarks and gluons in the proton that is less sensitive to final-state nonperturbative effects.

Plenary / **13**

Exotic and Conventional Quarkonium Physics Prospects at Belle II

Author: Ida Peruzzi[1]

[1] *Laboratori Nazionali di Frascati dell'INFN*

Corresponding Authors: tamponi@to.infn.it, peruzzi@slac.stanford.edu

The Belle II experiment at the SuperKEKB energy-asymmetric e^+e^- collider is a substantial upgrade of the B factory facility at the Japanese KEK laboratory. The design luminosity of the machine is 8×10^{35} cm^{-2}s^{-1} and the Belle II experiment aims to record 50 ab^{-1} of data, a factor of 50 more than its predecessor. From February to July 2018, the machine has completed a commissioning run and main operation of SuperKEKB has started in March 2019: first results on approx. $10fb^{-}1$ of data are expected by the end of June. 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. This talk will present the prospects of Belle II to explore both exotic and conventional quarkonium physics.

Parallel 3 / **14**

High-energy hadronic processes and parton distribution functions in the presence of Lorentz symmetry violation

Authors: Enrico Lunghi[1]; Nathan Sherrill[2]; V. Alan Kostelecky[2]; Alexandre Vieira[3]

[1] *Indiana University (US)*

[2] *Indiana University*

[3] *Universidade Federal do Triangulo Mineiro, Brazil*

Corresponding Authors: kostelec@indiana.edu, alexandre.vieira@uftm.edu, nlsherrill@gmail.com, elunghi@indiana.edu

Hadron-lepton and hadron-hadron interactions at large momentum transfer are studied in the presence of Lorentz-violating background fields affecting quarks. Connections are made with the operator-product expansion and leading-twist parton distribution functions are derived. Cross sections for deep inelastic scattering and the Drell-Yan process are calculated at leading order for minimal and nonminimal Lorentz violation using the Standard-Model Extension, an effective field theory characterizing general Lorentz-violating effects for the Standard Model fields and General Relativity. Estimated bounds are placed using sidereal-time analyses of existing HERA, LHC, and future US-based electron-ion collider data.

Parallel 3 / 15

Angular and energy dependence of Ay, Ayy and Axx analyzing powers in dp elastic scattering and dp breakup reaction investigation

Authors: Marian Janek[None]; Vladimir Ladygin[1]; Nadezhda Ladygina[2]; Alexander Averyanov[2]; Eugene Chernykh[2]; DAN DUMITRU ENACHE[3]; Yuri Gurchin[2]; Alexander Isupov[2]; Julia-Tatiana Karachuk[4]; Dimitry Krivenkov[2]; Pavel Kurilkin[2]; Alexei Livanov[2]; Olena Mezhenska[5]; Semen Piyadin[2]; Sergei Reznikov[2]; Yaroslav Skhomenko[2]; Arkady Terekhin[2]; Alexei Tishevsky[2]; Tomohiro Uesaka[6]

[1] *Joint Institute for Nuclear Research (JINR)*

[2] *JINR*

[3] *IFIN-HH ROMANIA*

[4] *National Institute for R&D in Electrical Engineering ICPE-CA*

[5] *P.-J. Safarik University, Slovakia*

[6] *Nishina Center for Accelerator-Based Science, RIKEN*

Corresponding Authors: vladimir.ladyguine@cern.ch, janek.marian@gmail.com, dan.enache@nipne.ro

Energy dependence of the vector Ay and tensor Ayy and Axx analyzing powers in deuteron-proton (dp) elastic scattering is investigated in the energy range from 400 MeV - 2000 MeV at large scattering angles. The detection of the dp elastic scattering events has been done by the coincident measurement of deuteron and proton in the the angular range of 60-135 deg. in the cm. The Ay, Ayy and Axx analyzing powers have been measured for the sixteen and fifteen angles defined by the position of the counters placed in the horizontal and vertical planes, respectively. Preliminary results of differential cross sections and analyzing powers for dp elastic scattering are compared with theoretical predictions based on relativistic multi-scattering model which includes besides single and double scattering terms also delta isobar excitation. Strong sensitivity to the short range spin structure of the isoscalar nucleon-nucleon correlations is observed in deuteron analyzing powers. There are interesting parts of deuteron proton breakup reaction phase space in which three nucleon forces, relativistic or coulomb effects can be studied separately. Preliminary results of the cross section for the dp breakup reaction have been obtained in the energy range from 300 - 500 MeV of incoming deuteron for particular detector configurations in which the sensitivity to the nucleon-nucleon, three nucleon forces as well as relativistic effects are assumed.

Plenary / 16

High energy scattering in QCD: from low to high Bjorken x

Author: Jamal Jalilian-Marian[1]

[1] *Baruch College*

Corresponding Author: jamal.jalilian-marian@baruch.cuny.edu

We propose and develop a new formalism that generalizes the Color Glass Condensate approach to high energy scattering by including both small and large x gluons in the wave function of a target proton or nucleus. This allows one to treat particle production at both low and high transverse momenta on the same footing. We illustrate the formalism by calculating the differential cross section for scattering of a quark (or gluon) on a target proton or nucleus and show that inclusion of both small and large x gluon modes in the target allows one to investigate forward-backward (in rapidity) asymmetries in high energy collisions. It also leads to both even and odd anisotropic flow coefficients v_n in proton-proton and proton-nucleus collisions as well as double spin asymmetry A_{LL} in polarized proton-proton (light nucleus) scattering. We comment on how the formalism can be extended to study structure functions as well as di-jet production in DIS at both low and high $x_Bjorken$.

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Prompt Photon Production as a probe of Gluon Sivers Function

Authors: Abhiram Kaushik B[1]; Anuradha Misra[2]; Rohini Godbole[1]; Siddhesh Padval[2]

[1] *Centre for High Energy Physics, Indian Institute of Science, Bangalore 560012, India*

[2] *Department of Physics, University of Mumbai, Mumbai 400098, India*

Corresponding Authors: siddheshspadwal@gmail.com, rohini@iisc.ac.in, misra@physics.mu.ac.in, abhiramk@iisc.ac.in

We explore the possibility of using transverse single spin asymmetries (TSSAs) arising in prompt photon production through scattering of unpolarized beams of protons/ photons off transversely polarized proton target as probes of Gluon Sivers Function (GSF). We present estimates of asymmetry at RHIC energy, both for direct and fragmentation contributions, using recent fits of GSF in case of $pp^{\uparrow}$ scattering. We present estimates of TSSA in the process $e + p^{\uparrow} \rightarrow \gamma + X$ using different parametrizations of quark and gluon Sivers function at EIC and J-lab energies and in different kinematic regions.

Parallel 2 / 19

Precision jet event shapes for future Electron-Ion-Collider

Authors: Daekyoung Kang[1]; Tanmay Maji[2]

[1] *IMP, Fudan University, China*

[2] *IMP, Fudan University, Shanghai*

Corresponding Authors: dkang@fudan.edu.cn, tanmay@fudan.edu.cn

We study angularity event shape for deep inelastic scattering (DIS) in the framework of soft-collinear effective theory (SCET) tool to push the frontier of the precision jet physics in the future Electron-Ion Collider (EIC). Angularity τ_a Depends On a continuous parameter 'a' whose limiting values at $a = 0$ and $a = 1$ provide 'thrust' and 'jet broadening' event shapes. The angularity cross-section is dominated by 2-jet region where one (beam) along the proton beam direction created by the initial state radiation (ISR) and another one (jet) created by the final state radiation (FSR). The region can be accurately described using SCET. The cross-section is factorized in terms of hard, jet, beam and soft functions using SCET The angularity beam function is first computed here at next-to-leading order (NLO). Our result includes summation of the large logarithms up to next-to-next leading logarithmic (NNLL) accuracy in resumed perturbation theory. We present numerical result For DIS angularity cross-section which is going to be explored by the future EIC.

Parallel 3 / 20

The fermion-scalar system in Minkowski space

Author: Giovanni Salmè[1]

Co-authors: Emanuele Pace [2]; Jorge Henrique Alvarenga Nogueira [3]; Tobias Frederico [4]; Valerio Gherardi [5]

[1] *INFN - Rome (Italy)*

[2] *Tor Vergata, Rome Univ. Italy*

[3] *Instituto Tecnológico de Aeronáutica & 'La Sapienza' Università di Roma & INFN, Sezione di Roma*

[4] *ITA - Brasil*

[5] *SISSA - Trieste, Italy*

Corresponding Authors: jorge.ifusp@gmail.com, vgherad@sissa.it, salmeg@roma1.infn.it, emanuele.pace@roma2.infn.it, tobias@ita.br

A first, but thorough investigation of a fermion-scalar bound system has been carried out by solving the Bethe-Salpeter equation in Minkowski space and using a ladder kernel containing a massive exchange of a scalar or a vector boson. The LF momentum distributions have been obtained, shedding light on the possibility to correlate the features of those quantities and the underlying dynamics.

Parallel 1 / 21

Epstein-Glaser's Causal Light-Front Field Theory

Authors: Oscar A. Sánchez[1]; Bruto Max Pimentel Escobar[1]; Daniel Eduardo Soto Barrientos[2]

[1] *Instituto de Física Teórica - UNESP*

[2] *Universidad Nacional de Ingeniería (UNI)*

Corresponding Authors: oacevedo.s94@gmail.com, dsotob@uni.edu.pe, b.m.pimentel@gmail.com

Epstein-Glaser's ideas for the formulation of a distributional well-defined perturbative causal field theory are developed in light-front dynamics over the invariant null-plane coordinatization introduced by Rohrlich. Explicitly, the causality theorems which warrant the method are shown to remain valid in that dynamics, and the causal distribution splitting formulae are re-derived in accordance with it, exhibiting important differences with respect to its instant dynamics version. Application of these splitting formulae to the commutation distributions of the fermion and radiation fields naturally leads to the well known instantaneous terms of their Feynman's propagators, while the scalar field's one retains its form from instant dynamics. Additionally, the developed method is applied to scalar QED at second order, taking for the first order distribution the interaction only with the linear in the coupling constant part of the current. We analyse Moeller's scattering, for which the equivalence with instant dynamics is established, and Compton's scattering, for which the vertex coming from the second order term in the current is automatically generated in the normalization procedure once the residual gauge invariance which remains from the imposition of the null-plane gauge condition is exploited.

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Sub-eikonal corrections and low-x helicity evolution

Author: Giovanni A. Chirilli[1]

[1] *University of Regensburg*

Corresponding Author: giovanni.chirilli@gmail.com

Most of the progress in high-energy Quantum Chromodynamics has been obtained within the eikonal approximation and infinite Wilson-line operators. Evolution equations of Wilson lines with respect to the rapidity parameter encode the dynamics of the hadronic processes at high energy. However, even at high energy many interesting aspects of hadron dynamics are not accessible within the eikonal approximation, the spin physics being an obvious example. The higher precision reached by the experiments and the possibility to probe spin dynamics at future Electron Ion Colliders make the study of deviations from eikonal approximation especially timely.

I will present the high-energy sub-eikonal corrections and the low-x helicity evolution through the high-energy Operator Product Expansion.

Parallel 3 / 23

Tetraquark properties at large N_c

Authors: Wolfgang Lucha[1]; Dmitri Melikhov[2]; Hagop Sazdjian[3]

[1] *Austrian Academy of Sciences*

[2] *HEPHY, Vienna, Austria and SINP, Moscow, Russia*

[3] *University Paris-Sud*

Corresponding Authors: dmitri_melikhov@gmx.de, sazdjian@ipno.in2p3.fr, wolfgang.lucha@oeaw.ac.at

The question of the existence of compact tetraquarks is studied in the large-N_c limit of QCD. Considering the fully exotic case, corresponding to four different quark flavors, it is shown that consistency conditions of correlation functions of color-singlet bilinear currents require the existence of two different tetraquarks, each decaying preferentially into a single two-meson channel. On the other hand, the diquark scheme, which provides the mechanism for producing compact tetraquarks, gives rise to one tetraquark bound state. This contradiction suggests that large-N_c QCD does not support the existence of compact flavor-exotic tetraquarks.
Based on Phys. Rev. D 98 (2018) 094011.

Parallel 2 / 24

Holographic light-front QCD in B meson phenomenology

Author: Mohammad Ahmady[1]

Co-author: Ruben Sandapen [2]

[1] *Mount Allison University*

[2] *Acadia University*

Corresponding Authors: ruben.sandapen@acadiau.ca, mahmady@mta.ca

The light-front wavefunctions for mesons obtained from holographic light-front QCD are used to obtain light-cone distribution amplitudes and transition form factors for B decays to light mesons. I present our predictions for some rare decay channels of B mesons.

Plenary / **25**

An overview of light-front holography

Author: Ruben Sandapen[1]

[1] *Acadia University*

Corresponding Author: ruben.sandapen@acadiau.ca

Light-front holography refers to an exact correspondance between semiclassical (with zero quark masses and no quantum loops) light-front QCD and a gravitational theory in 5-dimensional anti-de Sitter spacetime. Conformal symmetry is broken in a novel way, namely by the so-called dAFF (de Alfaro, Furbini and Furlan) mechanism which allows the emergence of a fundamental AdS/QCD mass scale κ in the Hamiltonian while retaining the conformal invariance of the action. The AdS/QCD scale κ sets the confinement scale as well as the mass scale for hadron spectroscopy in physical spacetime. Remarkably, the pion remains massless in the presence of a non-zero κ just as expected in QCD for massless quarks. Superconformal algebra allows a unified description of mesons, baryons and tetraquarks spectroscopy. The AdS/QCD scale κ is perhaps more fundamental than the familiar Λ_{QCD} scale which emerges due to dimensional transmutation in perturbative QCD. In fact, by matching of the κ-dependent running strong coupling in the infrared to the Λ_{QCD}-dependent running strong coupling in perturbative QCD, the latter scale can be predicted from the former. Light-front holography serves as an excellent first approximation to hadron physics. Going beyond the semiclassical approximation, quark masses and their spins can be taken into account *a posteriori*, leading to successful unified description of observables involving light pseudoscalar and vector mesons using a single universal value of the AdS/QCD scale κ. Light-front holographic wavefunctions also serve as basis functions for Basis Light-Front Quantization which is a promising method for investigating non-perturbative QCD.

Parallel 3 / **26**

Vector meson photoproduction in ultra-peripheral Pb-Pb collisions with ALICE at √sNN=5.02 TeV

Author: Valeri Pozdniakov[1]

[1] *Joint Institute for Nuclear Research (RU)*

Corresponding Author: valeri.pozdniakov@cern.ch

The study of photonuclear and two-photon interactions in ultra-peripheral collisions (UPC) is a tool to learn about the initial state of nuclei. In such collisions, the nuclei do not overlap and strong nuclear interactions are suppressed.

New ALICE results from LHC Run 2 are presented for forward J/ψ photoproduction, which is sensitive to the nuclear gluon distribution. The large data sample allows for a more detailed study of the cross section as a function of rapidity.

In addition, the analysis of the γ+A $\longrightarrow$ρ0+A process in UPC tests the black disk regime, where the target nuclei appears like a black disk and the total ρ0+A cross section reaches its limit. Cross sections of ρ0 photoproduction in Pb-Pb UPC are measured at mid-rapidity and compared to predictions based on the Glauber model and the color dipole approach.

Parallel 3 / 27

Non-perturbative studies of the three-boson system using the Bethe-Salpeter equation

Author: Emanuel Ydrefors[1]

Co-authors: Jorge Alvarenga Nogueira [2]; Vladimir Karmanov [3]; Tobias Frederico [4]; Jaume Carbonell [1]

[1] *Institut de Physique Nucléaire Orsay*

[2] *Instituto Tecnológico de Aeronautica*

[3] *Lebedev Physical Institute*

[4] *Instituto Tecnológico de Aeronáutica*

Corresponding Authors: ydrefors@kth.se, tobias@ita.br, karmanovva@lebedev.ru, jorge.ifusp@gmail.com, carbonell@ipno.in2p3.fr

Generally speaking, improving our understanding of the interaction in terms of the fundamental degrees of freedom is very important for nuclear and particle non-perturbative physics. As it is very involved problem, simple models are of great value for understanding the basic qualitative features of the solution for more realistic kernels. Unraveling the properties of relativistic three-body systems is also important, in particular, for the perspective of hadron physics, e.g. for the modeling of the nucleon and its dynamics. Moreover, it is well-established that in the non-relativistic approach the binding energy of this system is not bounded from below, what is known as Thomas collapse. As it was discovered in the light-front dynamics (LFD) [1,2], the relativistic repulsion prevents the Thomas collapse in the non-relativistic sense.

The Bethe-Salpeter (BS) equation constitutes a convenient approach to perform non-perturbative studies of few-body systems in Minkowski space. Calculations of that type is important in order to access dynamical observables, such as space-like and time-like form factors, which are defined exclusively in Minkowski space. In this contribution we will discuss the solutions of the bound-state Bethe-Salpeter equation (BSE) for a system of three bosons interacting through a zero-range interaction. This equation was solved in Minkowski space by Frederico in Ref. [1], and later improved by Carbonell and Karmanov in [2]. However, in these calculations the projection onto the light-front was adopted, retaining only the valence component of the BS amplitude. Recently, in Ref. [3], we solved the full three-body BS equation in Euclidean space, and it was found that contributions from higher Fock components have a dramatic effect, both on binding energies and transverse amplitudes. Even more recently, in Ref. [4], we solved the three-body BS equation in Minkowski space, by direct integration of the equation, similarly to the method introduced in [5] for the two-body system.
We compare the computed results for the three-body binding energies and transverse amplitudes, with the ones obtained in Euclidean space.
Our results show that, at least for moderate three-body binding energies, a fair agreement is found between the two methods, both for the binding energy and the modulus of the transverse amplitude. This is encouraging since the calculations based on direct integration of the BSE present many challenges, both from analytical and numerical points of view, due to the singularities of the kernel and the Bethe-Salpeter amplitude. To improve the numerical accuracy, one possibility could be to represent the three-body BS amplitude by the Nakanishi Integral Representation, and thus produce a non-singular equation. This is still work in progress, and will be briefly discussed.

Plenary / **28**

Light front quantum mechanics and quantum field theory

Author: Wayne Polyzou[1]

[1] *University of Iowa*

Corresponding Author: polyzou@uiowa.edu

I will give a short introduction to light-front formulations of relativistic quantum mechanics and quantum field theory. I will discuss some of the special properties and advantages of a light-front dynamics. I will also discuss both the relation to and differences with "instant-form" relativistic quantum mechanics and canonical formulations of quantum field theory.

Parallel 2 / **29**

Accessing Linearly Polarized Gluon Distribution in J/ψ Production at the Electron-Ion Collider

Author: Raj Kishore[1]

Co-author: Asmita Mukherjee [2]

[1] *Indian Institute of Technology*

[2] *IIT Bombay*

Corresponding Authors: raj.theps@gmail.com, asmita@phy.iitb.ac.in

We present an estimate of azimuthal asymmetry ($cos\ 2\phi$) in J/ψ production in electron-proton collision within the kinematics of the planned electron-ion collider (EIC). We find a small but a sizable asymmetry in the small x region which can be observed at the EIC. This sizable asymmetry directly probes the Weisz\"{a}ker-Williams (WW) type linearly polarized gluon distribution in unpolarized proton. We assume generalized factorization and calculate the asymmetry at next-to-leading order in the kinematical region which satisfies, energy fraction of J/ψ, $z < 1$ and the subprocess $\gamma^* + g \rightarrow c + \bar{c} + g$ gives the leading contribution. We use color-singlet model, based on non-relativistic QCD (NRQCD), for J/ψ production. We estimate the asymmetry in two models: (i) Gaussian type parameterization of the TMDs and (ii) McLerran-Venugopalan (MV) model at small x and also we present the upper bound of the asymmetry. All three cases estimate a small but sizable asymmetry in the considered kinematical region. So, observing a $cos\ 2\phi$ asymmetry in J/ψ production at EIC will give information on linearly polarized gluon distribution.

Plenary / **30**

Spin Physics at Hadron Facilities

Author: Oleg Eyser[1]

[1] *Brookhaven National Laboratory*

Corresponding Author: keyser@bnl.gov

The partonic structure of the proton has been established in deep inelastic scattering and a detailed picture of the nucleon has emerged from a wide range of experiments and global analyses. Hadronic

collisions allow direct access to the gluon content in the nucleon and polarized beams introduce an additional degree of freedom, spin, which is naturally connected to parton kinematics. Polarized proton collisions at RHIC have, for the first time, established a significant contribution of the gluon spin to the spin of the proton. They have similarly improved our knowledge of the sea quark polarization. In addition, transverse spin phenomena are enabling studies of transverse momentum dependent distribution functions and spin-orbit correlations beyond a one-dimensional image. At the same time, they are closely linked to questions about universality of the process dependence of color exchanges, factorization, and possibly saturation effects a very small partonic momenta.

Plenary / 31

Minkowski space approach to self-energies and scale invariance

Author: Tobias Frederico[1]

[1] *Instituto Tecnologico de Aeronautica*

Corresponding Author: tobias@ita.br

In this contribution the solution of the Schwinger-Dyson equation in Minkowski space, for a QED-like theory with a massive vector, in Rainbow ladder approximation and using integral representation will be presented for the Feynman gauge and compared to Euclidean results with Pauli-Villars regulators. The unregulated equations have solution below the critical coupling constant $\alpha_c = \frac{\pi}{4}$ before the Miransky scaling takes place. It is derived the power-law form of the spectral densities for $\alpha < \alpha_c$. It will be also discussed an analogous property, known for the Bethe-Salpeter equation applied to the fermion-fermion case, where for the stability of the bound state solution the coupling constant should be below a critical value due to the breaking of scale invariance, which will be discussed in the context of a fermion-boson BSE with vector exchange. The power law behavior of the asymptotic light-cone amplitudes will be compared to numerical results from the solution of the BSE in Minkowski space.
This contribution has the collaboration of J. H. de Alvarenga Nogueira, D. C. Duarte, S. Jia, P. Maris, W. de Paula, E. Pace, G. Salmè, and E. Ydrefors.

Parallel 2 / 33

3D imaging of the pion off-shell electromagnetic form factors

Author: Ho-Meoyng Choi[1]

Co-authors: Tobias Frederico [2]; Chueng Ji [3]; João Pacheco De Melo [4]

[1] *Kyungpook National University*

[2] *Instituto Tecnologico de Aeronautica*

[3] *North Carolina State University*

[4] *Universidade Cruzeiro do Sul*

Corresponding Authors: jpachecodm@gmail.com, tobias@ita.br, crji@ncsu.edu, homyoung@knu.ac.kr

The main tools to probe the structure of the hadron in terms of quarks and gluons are the electron elastic and inelastic scattering experiments. In the elastic case, the charge and current distributions of the on-mass-shell target hadron are encoded in the electromagnetic form factors which depend on the virtual photon four-momentum square $q^2 = -Q^2$. For the on-mass-shell spin-zero charged pion,
only one real form factor exists in the spacelike region $Q^2 > 0$ due do the time reversal invariance. Due to the short lifetime of the pion, however, the on-mass-shell elastic electron-pion scattering is

not yet feasible and thus one may resort to the pion electroproduction process to estimate the on-mass-shell pion form factor extrapolating the data with one leg off-mass-shell, $t \neq m_\pi^2$, in the limit $t \to m_\pi^2$. On the other hand, the kinematic region of the electroproduction process is intrinsically limited to $t < 0$ and the extrapolation to $t \to m_\pi^2$ involves the disallowed kinematic region of $t > 0$. In this work, we analyze the two off-shell pion form factors appearing in the matrix element of the pion electromagnetic current with one leg off-mass-shell using an exactly solvable manifestly covariant model of a $(3+1)$ dimensional fermion field theory and provide the 3D image of the two off-shell pion form factors as a function of (Q^2, t).

Parallel 2 / 34

Dissociative production of vector mesons as a new tool to study gluon saturation at electron-ion colliders

Author: Dagmar Bendova[1]

Co-authors: Jan Cepila [2]; Jesus Guillermo Contreras Nuno [2]

[1] *Czech Technical University in Prague (FNSPE)*

[2] *Czech Technical University (CZ)*

Corresponding Authors: jesus.guillermo.contreras.nuno@cern.ch, dagmar.bendova@fjfi.cvut.cz, jan.cepila@fjfi.cvut.cz

We present a model with which we predict the cross sections for exclusive and dissociative photo and electroproduction of light and heavy vector mesons off protons; the model describes correctly available experimental data. The model is based on the color-dipole approach and incorporates geometric fluctuations of the target-proton partonic structure. The fluctuations are generated as randomly placed areas of high gluonic density, so-called hot spots, in the proton impact-parameter plane, with the number of hot spots being energy-dependent. A striking feature of the model is the prediction of a maximum of the dissociative cross section as a function of the centre-of-mass energy W_{\gammap}, followed by a steep decrease as the hot spots start to overlap with increasing energy. We use these maxima to define a geometrical saturation scale and find that it grows linearly with energy as a function of the scale of the process. This phenomenon can be studied at the proposed electron-ion colliders, JLEIC, eRHIC and LHeC. We present a comparison of their envisioned kinematic reach with the geometrical saturation scale.

Parallel 2 / 35

Constraining gluon PDFs and TMDs with quarkonium production

Authors: Melih Arslan Ozcelik[1]; Cristian Pisano[2]; Miguel Echevarria[3]; Jean-Philippe Lansberg[4]; Andrea Signori[5]

[1] *Institut de Physique Nucleaire Orsay/Universite Paris-Sud/Unive*

[2] *University and INFN Cagliari (Italy)*

[3] *INFN Pavia*

[4] *IPN Orsay, Paris Saclay U. / IN2P3-CNRS*

[5] *Argonne National Laboratory*

Corresponding Authors: lansberg@in2p3.fr, dd46mi@mac.com, asignori@anl.gov, cristian.pisano@ca.infn.it, ozcelik@ipno.in2p3.fr

We explore how the positivity of the P_T-integrated η_c-hadroproduction cross-section computed at NLO in α_s can set up constraints on the x dependence of both gluon PDFs and TMDs at low scales.

Parallel 2 / **36**

Quark mass function from a OGE-type interaction in Minkowski space

Authors: Alfred Stadler[1]; Elmar Biernat[2]; Franz Gross[None]; M.T. Peña[None]

[1] *University of Évora*

[2] *Instituto Superior Tecnico, Universidade de Lisboa*

Corresponding Authors: stadler@uevora.pt, gross@jlab.org, elmar.biernat@tecnico.ulisboa.pt

I present results for the quark mass function in Minkowski space in both the spacelike and timelike regions calculated from the same quark-antiquark interaction kernel used in the latest meson calculations within the Covariant Spectator Theory. This kernel consists of a Lorentz vector effective one-gluon-exchange-type interaction, a vector constant, and a mixed scalar-pseudoscalar covariant linear confining interaction that does not contribute to the mass function. Our results are obtained in a general linear covariant gauge, their gauge dependence is analyzed and the Yennie gauge is identified as the appropriate gauge to be used in our calculations. Our results are compared in the spacelike region to the existing lattice QCD data and we find good agreement.

Parallel 3 / **37**

Lensing function relation in hadrons

Authors: Barbara Pasquini[1]; Simone Rodini[2]; Alessandro Bacchetta[3]

[1] *University of Pavia and INFN-Pavia*

[2] *University of Pavia & INFN Pavia*

[3] *University of Pavia*

Corresponding Authors: alessandro.bacchetta@unipv.it, pasquini@pv.infn.it, simone.rodini01@universitadipavia.it

The parton structure of the proton can be studied mainly using two types of hard scattering processes: exclusive processes, giving access to Generalised 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 [1]. In this talk, I will discuss the general features of model calculations that allow to establish this so-called lensing relation [2]. I will also discuss two specific examples in the framework of light-front quantisation: the pion, as a prototype of a two-body bound system where the lensing relation holds, and the proton, viewed as a three-body bound system, where the relation is broken.
[1] M. Burkardt, Phys. Rev. D66 (2002) 114005
[2] B. Pasquini, S. Rodini, A. Bacchetta, arXiv:1907.06950

Plenary / **38**

Hadronic Properties from Basis Light Front Quantization

Author: James Vary[1]

[1] *Iowa State University*

Corresponding Author: jvary@iastate.edu

Basis Light Front Quantization provides a practical framework and is actively used for solving the mass eigenvalue problem of the light-front Hamiltonian for hadronic systems. I will review recent results for mixed-flavor and light mesons as well as for baryons. These results include masses, decay constants, transition rates, form factors, parton distribution functions including their QCD evolution, transverse momentum distributions, non-perturbative time-dependent scattering amplitudes and others. Comparisons with experimental data as well as with results from Lattice QCD and the Dyson-Schwinger approach will be presented where available. Prospects for applications to more complex multi-quark and multi-gluon systems will be outlined.

Plenary / **39**

Complex poles, spectral function and reflection positivity violation of Yang-Mills theory

Author: Kei-Ichi Kondo[1]

[1] *Chiba University*

Corresponding Author: kondok@faculty.chiba-u.jp

We consider the analytic continuation of the gluon propagator from the Euclidean region to the complex momentum plane towards the Minkowski region. Then we derive general relationships between the number of complex poles of a propagator and the sign of the spectral function originating from the branch cut in the Minkowski region under some assumptions on the asymptotic behaviors of the propagator.
We apply this relation to the massive Yang-Mills model with one-loop quantum corrections, which is to be identified with a low-energy effective theory of the Yang-Mills theory in the sense that the confining decoupling solution for the Euclidean gluon and ghost propagators of the Yang-Mills theory in the Landau gauge obtained by numerical simulations on the lattice are reproduced with good accuracy from the massive Yang-Mills model by taking into account one-loop quantum corrections.
We show that the gluon propagator in the massive Yang-Mills model has a pair of complex conjugate poles or "tachyonic" poles of multiplicity two, in accordance with the fact that the gluon field has a negative spectral function, while the ghost propagator has at most one "unphysical" pole. Consequently, we give an analytical proof that the reflection positivity is violated for any choice of the parameters in the massive Yang-Mills model, including the physical point. The complex structure of the propagator enables us to explain why the gluon propagator in the Euclidean region is well described by the Gribov-Stingl form.
Moreover, we show that massive Yang-Mills model is obtained as a gauge-fixed version of the gauge-invariantly extended theory which is identified with the gauge-scalar model with a single fixed-modulus scalar field in the fundamental representation of the gauge group. This equivalence is obtained through the gauge-independent description of the Brout-Englert-Higgs mechanism proposed recently by the author.

Parallel 1 / **40**

Chiral symmetry restoration and the thermal $f_0(500)$ state.

Authors: Andrea V. Rodríguez[1]; Angel Gomez Nicola[2]

[1] *Universidad Complutense de Madrid*

[2] *Universidad Complutense Madrid*

Corresponding Authors: gomez@fis.ucm.es, avioque@ucm.es

We analize the role played by the thermal $f_0(500)$ state or σ in chiral symmetry restoration. The temperature corrections to the spectral properties of that state are included in order to provide a better description of the scalar susceptibility χ_S around the transition region. We use the Linear Sigma Model to establish the relation between χ_S and the σ propagator, which is used as a benchmark to test the approach where χ_S is saturated by the $f_0(500)$ inverse self-energy. Within such saturation approach, a peak for χ_S around the chiral transition is obtained when considering the $f_0(500)$ generated as a $\pi\pi$ scattering pole within Unitarized Chiral Perturbation Theory at finite temperature. That approach yields results complying with lattice data when the uncertainties of the low-energy constants are taken into account. Those uncertainties and the unitarization method are used to check the robustness of this approximation. A comparison with the Hadron Resonance Gas is also studied in this context. Finally, we will discuss some recent results within the chiral lagrangian framework related to the topological susceptibility and its connection with chiral and $U_A(1)$ restoration.

Parallel 2 / 41

The dipole picture and the non-relativistic expansion

Author: Miguel A. Escobedo[1]

Co-author: Tuomas Lappi [2]

[1] *IGFAE-Universidade de Santiago de Compostela*

[2] *University of Jyväskylä*

Exclusive quarkonium production offers one of the best ways to obtain information about gluon distributions at small x, in ultraperipheral heavy-ion collisions and deep inelastic scattering. The quarkonium light-cone wave functions needed in the dipole picture have typically been available only at tree level, either in phenomenological models or in the nonrelativistic limit. In this talk, we discuss the compatibility of the dipole approach and the non-relativistic expansion and compute NLO relativistic corrections to the quarkonium light-cone wave function in light-cone gauge. Using these corrections we recover results for the NLO decay width of quarkonium to e^+e^- and we check that the non-relativistic expansion is consistent with ERBL evolution and with B-JIMWLK evolution of the target. The results presented here will allow computing the exclusive quarkonium production rate at NLO once the one loop photon wave function with massive quarks, currently under investigation, is known.

Parallel 1 / 42

Exploring pion and nucleon structure through basis light front quantization

Authors: Chandan Mondal[1]; Siqi Xu[2]; Jiangshan Lan[3]; Shaoyang Jia[4]; Sreeraj Nair[3]; Xingbo Zhao[1]; James Vary[4]

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

[2] *Institute of Modern Physics, CAS*

[3] *Institute of Modern Physics,CAS*

[4] *Iowa State University*

Corresponding Authors: xbzhao@impcas.ac.cn, mondal@impcas.ac.cn, jvary@iastate.edu

Basis light-front quantization is a nonperturbative approach which has been developed for solving many-body bound state problems in quantum field theories. We have applied this approach to investigate the structure of the pion using a light front effective Hamiltonian in the constituent quark-antiquark representation. The remarkable results for the electromagnetic (EM) form factor,

distribution amplitudes (DAs), Parton distribution functions (PDFs), pion to photons transition form factor, etc. confirm the robust character of this novel approach. We also investigate several aspects of the nucleon properties such as EM and axial form factors, PDFs, generalized Parton distributions (GPDs), etc. using the framework of BLFQ. We consider the light-front wavefunctions obtained by diagonalizing an effective Hamiltonian consisting of the holographic QCD confinement potential, longitudinal confinement, and a one-gluon exchange interaction with fixed coupling.

Plenary / **43**

QCD at finite temperature and density from the Curci-Ferrari model

Author: Urko Reinosa[1]

[1] *CPHT - Ecole Polytechnique - CNRS*

Corresponding Author: ureinosa@gmail.com

We review recent progress in describing the equilibrium properties of QCD (and related theories such as Yang-Mills theory) at finite temperature/density from a systematic and controlled small parameter expansion, based on the Curci-Ferrari model. The latter has recently been proposed as a possible extension of the standard but ill-defined Faddeev-Popov action in the Landau gauge. In the case of pure YM, it allows in particular to extend the validity of perturbation theory to the infrared regime. We shall review the predictions of this extended perturbation theory for the phase structure of YM theories and QCD in the formal regime of heavy quark flavors. We shall also discuss some preliminary applications of our framework to the physical QCD case.

Parallel 2 / **44**

Making Sense of the Nambu-Jona-Lasinio Model via Scale Invariance

Author: Philip Mannheim[1]

[1] *University of Connecticut*

Corresponding Author: philip.mannheim@uconn.edu

The status of the chiral-invariant Nambu-Jona-Lasinio (NJL) four-fermi model is quite equivocal. It serves as the paradigm for dynamical symmetry breaking and yet it is not renormalizable. NJL only studied one loop graphs with point vertices, and needed to use an ultraviolet cutoff. We propose to dress the point vertices with scale invariant vertices with anomalous dimensions. We show that if the dimension of the $\bar{\psi}\psi$ fermion mass operator is reduced from a canonical three to a dynamical two, the four fermion interaction becomes renormalizable to all orders in the four-fermion coupling constant. Additionally, we find that dynamical symmetry breaking then occurs with the fermion becoming massive, and we obtain a dynamical massless pseudoscalar Goldstone boson and a dynamical scalar Higgs boson. The Higgs boson mass is automatically of order the dynamical fermion mass, with there thus being no hierarchy problem. The Higgs boson automatically has a width, and the width could serve as a diagnostic to distinguish a dynamical Higgs from an elementary one. We extend the scale invariance to local conformal invariance as then coupled to a gravity theory, conformal gravity, that is conformal too. With Bender and Mannheim having shown that conformal gravity is a ghost-free, unitary theory, it can serve as a consistent theory of quantum gravity. We show that all of the achievements of supersymmetry can be achieved by conformal symmetry and conformal gravity instead, with there then being no need for any new particles at the LHC.

Plenary / 45

Beam spin asymmetry in the electroproduction of a pseudoscalar meson or a scalar meson off the scalar target

Authors: Chueng-Ryong Ji[None]; Ho-Meoyng Choi[1]; Andrew Lundeen[2]; Bernard L. G. Bakker[3]

[1] *Kyungpook National University*

[2] *NCSU*

[3] *Vrije Universiteit*

Corresponding Authors: crji@ncsu.edu, homyoung@knu.ac.kr

We discuss the electroproduction of a pseudoscalar (0−+) meson or a scalar (0++) meson off the scalar target. The most general formulation of the differential cross section for the 0−+ or 0++ meson process involves only one or two hadronic form factors, respectively, on a scalar target. The Rosenbluth-type separation of the differential cross section provides the explicit relation between the hadronic form factors and the different parts of the differential cross section in a completely model-independent manner. The absence of the beam spin asymmetry for the pseudoscalar meson production provides a benchmark for the experimental data analysis. The measurement of the beam spin asymmetry for the scalar meson production may also provide a unique opportunity not only to explore the imaginary part of the hadronic amplitude in the general formulation but also to examine the significance of the chiral-odd generalized parton distribution (GPD) contribution in the leading-twist GPD formulation.

Plenary / 46

Color Confinement and Supersymmetric Properties of Hadron Physics from Light-Front Holography

Author: Stanley Brodsky[1]

[1] *SLAC National Accelerator Laboratory*

Corresponding Author: sjbth@slac.stanford.edu

QCD is not supersymmetrical in the traditional sense – the QCD Lagrangian is based on quark and gluonic fields – not squarks or gluinos. However, its hadronic eigensolutions conform to a representation of superconformal algebra, reflecting the underlying conformal symmetry of chiral QCD and its Pauli matrix representation. The eigensolutions of superconformal algebra provide a unified Regge spectroscopy of meson, baryon, and tetraquarks of the same parity and twist as equal-mass members of the same 4-plet representation with a universal Regge slope. The pion $q\bar{q}$ eigenstate has zero mass for $m_q = 0$. The superconformal relations also can be extended to
heavy-light quark mesons and baryons. The combined approach of light-front holography and superconformal algebra also provides insight into the origin of the QCD mass scale and color confinement. A key tool is the remarkable dAFF principle which shows how a mass scale can appear in the Hamiltonian and the equations of motion while retaining the conformal symmetry of the action. When one applies the dAFF procedure to chiral QCD, a mass scale κ appears which determines universal Regge slopes, hadron masses in the absence of the Higgs coupling. The predictions from light-front holography and superconformal algebra can also be extended to mesons, baryons, and tetraquarks with strange, charm and bottom quarks.
Although conformal symmetry is strongly broken by the heavy quark mass, the basic
underlying supersymmetric mechanism, which transforms mesons to baryons (and baryons to tetraquarks), still holds and gives remarkable mass degeneracy across the entire spectrum of light, heavy-light and double-heavy hadrons. One also predicts the form of the nonperturbative QCD running coupling: $\alpha_s(Q^2) \propto \exp -Q^2/4\kappa^2$, in agreement with the effective charge determined from measurements of the Bjorken sum rule. One also obtains viable predictions for spacelike and timelike hadronic form factors, structure functions, distribution amplitudes, and transverse momentum distributions.

Parallel 1 / 49

Boson Stars and QCD Boson Stars

Author: Usha Kulshreshtha[1]

[1] *Kirori Mal College, University of Delhi*

Corresponding Author: ushakulsh@gmail.com

In this talk I will consider the boson stars in a theory of complex scalar filed in the presence of gravity and the the U(1) gauge field and the gluon field. I will discuss the results for the phase diagrams of the boson star solutions in this theory.

Parallel 1 / 50

Role of Light-Front Coordinates in String Theory

Author: Daya S. Kulshreshtha[1]

[1] *University of Delhi*

Corresponding Author: daya.kulsh@gmail.com

In this talk I would consider in details the role of the light-front coordinates in string theory.

Parallel 1 / 51

Going off the light-cone - a model study of quasi-GPDs

Author: Shohini Bhattacharya[1]

Co-authors: Christopher Cocuzza [1]; Andreas Metz [2]

[1] *Temple University*

[2] *Temple University, Philadelphia*

Corresponding Authors: metza@temple.edu, tug23108@temple.edu, tug83224@temple.edu

Studying light-cone PDFs through Euclidean correlators is currently an active field of research. In particular, the concept of quasi parton distributions (quasi-PDFs) is at the forefront of numerical calculation of partonic structure of strongly interacting systems on lattice using QCD. Quasi-PDFs converge to their respective standard distributions if the hadron momentum goes to infinity. We investigate this quasi-distribution approach for twist-2 generalized parton distributions (GPDs) in the widely-used diquark spectator model. We illustrate analytical and numerical results of quasi-GPDs and of quasi-PDFs. Our focus is to test how well the quasi-distributions agree with their standard counterparts for finite hadron momenta. Furthermore, we explore higher-twist effects associated with the parton momentum and the longitudinal momentum transfer to the target. By discussing the sensitivity of our results to model parameters, we highlight robust features of the quasi-GPDs and quasi-PDFs that one may extract from this model study. We also elaborate on a model-independent analysis of moments of quasi-distributions including relation to Ji's spin-sum rule. The moment analysis suggests a preferred definition of several quasi-distributions.

Plenary / 52

Frame dependence of transition form factors in light-front dynamics

Author: Meijian Li[1]

Co-authors: James Vary [1]; Pieter Maris [1]; Yang Li [1]

[1] *Iowa State University*

Corresponding Authors: leeyoung@iastate.edu, meijianl@iastate.edu, pmaris@iastate.edu, jvary@iastate.edu

We calculate the transition form factor between vector and pseudoscalar quarkonia in both the timelike and the spacelike region using light-front dynamics. We investigate the frame dependence of the form factors for heavy quarkonia with light-front wave functions calculated from the valence Fock sector. This dependence could serve as a measure for the Lorentz symmetry violation arising from the Fock-space truncation. We suggest using frames with minimal longitudinal momentum transfer for calculations in the valence Fock sector, namely, the Drell-Yan frame for the spacelike region and a specific longitudinal frame for the timelike region; at $q^2 = 0$ these two frames give the same result. We also use the transition form factor in the timelike region to investigate the electromagnetic Dalitz decay $\psi_A \to \psi_B l^+ k^- (l = e, \mu)$ and predict the effective mass spectrum of the lepton pair.

Plenary / **53**

Overview of TMDs

Author: Miguel Echevarria[1]

[1] *INFN Pavia*

Corresponding Author: dd46mi@mac.com

I will review the current status of transverse-momentum-dependent parton distribution and fragmentation functions (TMDs), which encode the 3-dimensional structure of the nucleon in momentum space. I will discuss their properties, how they are connected to different physical observables, and the state-of-the-art theoretical and phenomenological results.

Parallel 1 / **55**

$\pi\pi$ scattering on a renormalized Hamiltonian matrix

Author: Maria Gomez-Rocha[1]

Co-author: Enrique Ruiz Arriola [2]

[1] *University of Granada*

[2] *Universidad de Granada*

Corresponding Authors: earriola@ugr.es, mariagomezrocha@gmail.com

A Wilsonian approach to $\pi\pi$ scattering based in the Glazek-Wilson Similarity Renormalization Group for Hamiltonian is analyzed in the JI =00, 11 and 20 channels in momentum space up to a maximal CM energy of $\sqrt{s} = 1.4$ GeV. We identify the Hamiltonian by means of the 3D reduction of the Bethe-Salpeter equation in the Kadyschevsky scheme. We propose a new method to integrate the SRG equations based in the Crank-Nicolson algorithm with a single step finite difference so that sospectrality is preserved at any step of the calculations. We discuss issues on the high momentum tails present in the fitted interactions hampering calculations.

Parallel 1 / 56

The massive gluon and the massless pion

Author: Julien Serreau[1]

[1] *Université Paris Diderot*

Corresponding Author: serreau@apc.univ-paris7.fr

Lattice simulations of Yang-Mills theories and QCD in the Landau gauge demonstrate that the gluon propagator saturates at vanishing momentum. This can be modelled by a massive deformation of the corresponding Faddeev-Popov Lagrangian known as the Curci-Ferrari model. The latter does not modify the known ultraviolet regime of the theory and provides a successful perturbative description of essential aspects of the non-Abelian dynamics in the infrared regime, where, in particular, the coupling remains finite, as also seen in lattice simulations. This opens the possibility of a controlled (semi)perturbative description of various aspects of the infrared QCD dynamics, including correlation functions and the deconfinement phase transition at finite temperature and density. I present recent progress concerning the description of chiral symmetry breaking in this context.

Parallel 1 / 57

A new method to compute GPDs

Author: Cédric Mezrag[1]

[1] *INFN Roma 1*

Corresponding Author: cedric.mezrag@roma1.infn.it

Parallel 1 / 58

Getting access to generalized parton distributions in exclusive photoproduction of a large invariant mass gamma-meson pair

Authors: Renaud Boussarie[1]; Goran Duplancic[2]; Kornelija Passek-Kumericki[3]; Bernard Pire[None]; Lech Szymanowski[4]; Samuel Wallon[None]

[1] *Brookhaven National Lab*

[2] *Institute Ruder Boskovic, Zagreb*

[3] *Rudjer Boskovic Institute, Zagreb, Croatia*

[4] *National Centre for Nuclear Research*

Corresponding Authors: pire@cpht.polytechnique.fr, lech.szymanowski@ncbj.gov.pl, rboussarie@bnl.gov, passek@irb.hr, gorand@thphys.irb.hr, wallon@th.u-psud.fr

In the framework of collinear QCD factorization, we study the
photoproduction of a gamma meson pair with a large invariant mass and a small transverse momentum, as a new way to access generalized parton distributions (GPDs), in both chiral-even and chiral-odd sectors. In the kinematics of JLab˜12-GeV, we demonstrate the feasibility of this measurement.

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Exclusive diffractive processes including saturation effects at next-to-leading order

Authors: Renaud Boussarie[1]; Andrey Grabovsky[2]; Lech Szymanowski[3]; Samuel Wallon[None]

[1] *Brookhaven National Lab*

[2] *Budker Institute of Nuclear Physics*

[3] *National Centre for Nuclear Research*

Corresponding Authors: rboussarie@bnl.gov, wallon@th.u-psud.fr, lech.szymanowski@ncbj.gov.pl, a.v.grabovsky@inp.nsk.su

In the framework of the QCD shock-wave approach, we review our results on the description of diffractive production of various final states (jets, meson) at next-to-leading order. This is applied to the description of exclusive diffractive dijet electroproduction at HERA.

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Model expression for the Potential Angular Momentum in the LC-Gauge

Authors: Matthias Burkardt[None]; Cédric Lorcé[1]; Arturo Amor[1]

[1] *Ecole polytechnique*

Corresponding Authors: cedric.lorce@polytechnique.edu, arturo.amor-quiroz@polytechnique.edu, burkardt@nmsu.edu

The most common decompositions of angular momentum are the Jaffe-Manohar (canonical) and Ji (kinetic) decompositions, which differ by the potential angular momentum and depend on how the contributions are attributed to quarks and gluons. Lattice calculations has shown that difference between such decompositions is non-zero.

We justify using perturbation theory within a simple scalar diquark model at two-loop level the physical interpretation of a non-vanishing potential angular momentum as originating from the torque exerted by initial or final state interactions encoded in the light-cone gauge at light-cone infinity.

Parallel 3 / 61

EM form factors of purely relativistic systems

Author: Vladimir Karmanov[1]

Co-authors: Jaume Carbonell [2]; Hagop Sazdjian [3]

[1] *Lebedev Physical Institute*

[2] *IPNO, Univ. Paris-Sud, CNRS/IN2P3, Universit\'e Paris-Saclay*

[3] *IPNO, Univ. Paris-Sud, CNRS/IN2P3, Universite Paris-Saclay*

Corresponding Authors: karmanovva@lebedev.ru, sazdjian@ipno.in2p3.fr, carbonell@inpo.in2p3.fr

In the Wick-Cutkosky model [1,2] (two scalar particles interacting by massless exchange), for enough large coupling constant ($\alpha > \frac{\pi}{4}$), there exist two different types of solutions of the Bethe-Salpeter

equation [3]. Some solutions turn, in the non-relativistic limit, into the well-known Coulombien ones; other solutions, on the contrary, disappear in the non-relativistic limit (pushed out from the discrete spectrum). The latter ones have purely relativistic origin and are called "abnormal". We have shown [4] that similar abnormal solutions of the Bethe-Salpeter equation exist also for the massive exchange (for which the strong coupling constant is more realistic), that makes probable their existence in the nature.

In the present talk, we report some results of our study of the properties of these new states. Still in the Wick-Cutkosky model, in particular, for the coupling constant $\alpha = 5$, we found that the ground state (which is normal) is accompanied by two excited abnormal states. We calculated the elastic EM form factors for all these states and also the transition form factors between all of them. We found that the form factors for the abnormal states vs. momentum transfer Q^2 decrease much more faster than for the normal one. In this model, the ground state form factor has no nodes, whereas the form factor for the first abnormal state has one node, the form factor for the second abnormal state (next excited state) has two nodes.

[1] G.C. Wick, Phys. Rev. **96**, 1124 (1954).
[2] R.E. Cutkosky, Phys. Rev. **96**, 1135 (1954).
[3] E.E. Salpeter, H. Bethe, Phys. Rev. **84**, 1232 (1951).
[4] V.A. Karmanov, J. Carbonell and H. Sazdjian, *Abnormal relativistic states*, talk at LC18, JLAB (2018).

Parallel 1 / 62

Some subtleties of light-front quantization

Author: Lubomir Martinovic[1]

[1] *LTF JINR Dubna and Inst. of Physics SAS Bratislava*

Corresponding Author: fyziluma@savba.sk

We give a survey of a few subtle mathematical points whose correct treatment is necessary for obtaining noncontradictory structure of the front form of the field theory and its physical predictions. First, we show that small imaginary parts in the exponents of the light-front (LF) two-point functions (convergence factors) are mandatory for their correct equal-LF time limit and for vanishing of the surface terms in the Poincare algebra. The same mechanism removes unwanted terms in the transformation law of the scalar LF field under some Poincare generators. We also demonstrate that contrary to recent claims the LF Hamiltonian approach does not fail in the vacuum sector and actually yields results in agreement with the Feynman diagram method. The non-vanishing LF vacuum bubbles found recently within the Hamiltonian LF perturbation theory are shown to not violate conservation of the LF momentum. Their presence and analytical form agrees with the LF evaluation of the corresponding Feynman diagrams.

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Singularities in Twist-3 Quark Distributions

Authors: Fatma Aslan[1]; Matthias Burkardt[1]

[1] *NMSU*

Corresponding Authors: burkardt@nmsu.edu, fpaslan@nmsu.edu

We find in one-loop calculations and spectator models that twist-3 GPDs exhibit discontinuities. In the forward limit, these discontinuities grow into Dirac delta functions which are essential to satisfy the sum rules involving twist-3 PDFs. We calculate twist-3 quasi-PDFs as a function of longitudinal

momentum, and identify the Dirac delta function terms with momentum components in the nucleon state that do not scale as the nucleon is boosted to the infinite momentum frame.

Plenary / **66**

Bound states and Perturbation theory

Author: Paul Hoyer[1]

[1] *University of Helsinki*

Corresponding Author: paul.hoyer@helsinki.fi

QED bound states (atoms) are "non-perturbative"in the sense that no finite order Feynman diagram has a bound state pole. Wave functions are typically gauge dependent and exponential in α. Physical binding energies on the other hand do have a perturbative expansion in α (and log α). The hyperfine splitting of Positronium has been evaluated to O($\alpha^7 \log\alpha$) and agrees with data, whose accuracy is of O(10^{-10}). Thus "non-perturbative"need not imply that a perturbative expansion is irrelevant. This may hold also for QCD hadrons: Their initial wave functions can have non-perturbative features (confinement, chiral symmetry breaking), with corrections expressed in powers of $\alpha_s/\pi \sim 0.16$.

The standard method for atoms is to evaluate Feynman diagram corrections to an assumed wave function (typically the Schrödinger one). In a Hamiltonian approach the expansion is instead formulated in terms of Fock states. In temporal ($A^0 = 0$) gauge higher Fock states are suppressed by powers of α. For Positronium the $|e^+e^-\rangle$ Fock state is bound by the instantantaneous longitudinal electric field E_L, giving a Schrödinger wave function. The $|e^+e^-\gamma\rangle$ state with a transverse photon is suppressed by α and gives rise to hyperfine splitting, and so on.

In temporal gauge Gauss'law appears as a constraint on physical states, which serves to completely fix the gauge, i.e., E_L. In QCD the Gauss constraint allows solutions with a spatially constant, O(α_s^0) longitudinal color electric field E_L^a for each Fock component, e.g., for a $|q^C\bar{q}^C\rangle$ meson Fock state. The field vanishes when summed over the color C for (globally) color singlet states, and is thus invisible to an external observer. However, it generates a linear potential for each $|q^C\bar{q}^C\rangle$ component. The outcome is reminiscent of the MIT bag model, which postulates a non-vanishing field energy density for the vacuum. Now there is no fixed bag boundary so Poincar\'e invariance is intact: the quarks move in the confining field rather than in a field-free bubble. The single energy scale Λ is fixed by the vacuum field energy density.

The strong O(α_s^0) potential confines charges even though α_s is small. The potential of any Fock state, e.g., $|q^Aq^Bq^C\rangle$ (baryons),$|q^Aq^Bg^a\rangle$ (mesons with a transverse gluon) and $|g^ag^a\rangle$ (glueballs) are given in terms of Λ by the Gauss constraint. The Hamiltonian defines hadrons of any momentum P. The potential is determined by the instantaneous positions of the charges and is thus independent of P. Details may be found in arXiv:1807.05598v2.

Parallel 3 / **67**

Constraints on the Intrinsic Charm Content of the Proton from Recent ATLAS Data

Authors: Gennady Lykasov[1]; Juraj Smiesko[2]; Stanly Brodsky[3]; Vadim Bednyakov[1]

[1] *Joint Institute for Nuclear Research*

[2] *Comenius University in Bratislava, Faculty of Mathematics, Physics and Informatics*

[3] *SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94025, United States*

Corresponding Authors: juraj.smiesko@cern.ch, gennady.lykasov@cern.ch, vadim.bednyakov@cern.ch, sjbth@slac.stanford.edu

Intrinsic heavy quarks contributions to the nonperturbative structure of hadrons is a rigorous property of light-front wavefunctions in QCD.
The intrinsic distributions scale as $1/m_Q^2$ and are maximal at minimal off-shellness; i.e., equal rapidity and thus
$x_Q \propto \sqrt{m_Q^2 + k_{\perp Q}^2}$.
An empirical constraint on the intrinsic charm (IC) probability in the proton is found
using recent ATLAS data for the associated production of prompt photons and
charm-quark jets in pp collisions at $\sqrt{s} = 8$˜TeV. An upper
limit of 1.93˜\% is obtained at the 68˜\% confidence level.
Methods for reducing the scale and systematical
experimental uncertainties are discussed. The implications of
intrinsic heavy quarks in the light-front wavefunction of the proton for future studies at the LHC are also
discussed. In particular, new predictions based on the IC contribution
in the hard production of the Z boson associated with a charm quark jet are presented.

Plenary / **68**

An overview of baryon-to-meson Transition Distribution Amplitudes: basic properties, physical interpretation and experimental perspectives

Author: Kirill Semenov-Tian-Shansky[1]

Co-authors: Bernard Pire [2]; Lech Szymanowski [3]

[1] *PNPI*

[2] *CPHT école polytechnique*

[3] *National Centre for Nuclear Research*

Corresponding Authors: lech.szymanowski@ncbj.gov.pl, cyrstsh@gmail.com, bernard.pire@polytechnique.edu

Baryon-to-meson Transition Distribution Amplitudes (TDAs) appear as building blocks for amplitudes within the collinear factorized description of a class of hard exclusive reactions such as hard exclusive meson electroproduction off a baryon in the near-backward region and baryon-antibaryon annihilation into a meson and a lepton pair.

In this talk we present a general overview of the fundamental properties of baryon-to-meson TDAs and address their physical contents with a particular emphasize on the interpretation in the impact parameter space. We also discuss the observable quantities sensitive to the onset of the collinear factorization regime for the corresponding hard exclusive reactions and consider experimental perspectives for accessing baryon-to-meson TDAs at JLab and at future experimental facilities such as PANDA@GSI-FAIR and EIC.

Plenary / **69**

Overview of small-x physics and TMDs

Author: Tolga Altinoluk[1]

[1] *National Centre for Nuclear Research*

Corresponding Author: tolga.altinoluk@ncbj.gov.pl

Inclusive particle production in forward pA collisions is one of the observables that is used frequently in order to understand the high-energy collision data. Moreover, at certain kinematics, one gets access to TMDs from the CGC calculations of these observables. I will discuss the details of this correspondence focusing on multi-jet production.

Plenary / **70**

Confinement in Nuclei and the Expanding Proton

Author: Gerald Miller[1]

[1] *University of Washington, Seattle*

Corresponding Author: miller@uw.edu

High-precision knowledge of electromagnetic form factors of nuclei is a subject of much current experimental and theoretical activity in nuclear and atomic physics. Such precision mandates that effects of the non-zero spatial extent of the constituent nucleons be handled in a manner that goes beyond the usual impulse approximation. A series of simple, Poincare-invariant, composite-proton models that respect the Ward-Takahashi identity and in which quarks are confined are used to study the validity of this approximation. The result of all of the models is a general theorem showing that medium modification of proton structure must occur. Combining this result with lattice QCD calculations leads to a conclusion that a bound proton must be larger than a free one.

Parallel 2 / **71**

How to include exclusive J/psi production data in global PDF analyses

Authors: Alan Martin[None]; Chris Flett[None]; Misha Ryskin[1]; Stephen Philip Jones[2]; Thomas Teubner[3]

[1] *Petersburg Nuclear Physics Institute*

[2] *CERN*

[3] *University of Liverpool*

Corresponding Authors: a.d.martin@durham.ac.uk, thomas.teubner@liverpool.ac.uk, ryskin@thd.pnpi.spb.ru, c.a.flett@liverpool.ac.uk, s.jones@cern.ch

We compare the cross section for exclusive J/ψ photoproduction calculated in the NLO collinear factorization approach with HERA and LHCb data. We use the optimum scale formalism together with the subtraction of the low $k_t < Q_0$ contribution from the NLO coefficient function to avoid a crucial double counting and show that the existing global parton distribution functions (PDFs) are consistent with the data within their uncertainties. However, at low x the uncertainties of the present global PDFs are huge while the accuracy of the LHCb data is rather good. Therefore, for the first time, these data provide the possibility to directly measure the gluon PDF over the very large interval of x, $10^{-6} < x < 10^{-2}$, at a fixed low scale.

Parallel 3 / **73**

Gravitational form factor constraints and their universality

Author: Peter Lowdon[None]

Co-authors: sabrina cotogno [1]; Cédric Lorcé [2]

[1] *Nikhef*

[2] *Ecole polytechnique*

Corresponding Authors: cedric.lorce@polytechnique.edu, scotogno@nikhef.nl, peter.lowdon@polytechnique.edu

In this talk I will discuss the constraints imposed by Poincaré symmetry on the form factors appearing in the Lorentz decomposition of the energy-momentum tensor matrix elements. By adopting a distributional approach, one can prove non-perturbatively that the zero momentum-transfer limits of the leading two form factors are completely independent of the properties of the states in the matrix elements. I will briefly outline some of the consequences of this state universality.

Plenary / **74**

Energy-Momentum Tensor and Light Cone

Author: Oleg Teryaev[1]

[1] *JINR*

Corresponding Author: teryaev@theor.jinr.ru

The QCD energy-momentum tensor (EMT) relation to light-cone distributions and correlators is considered. The limit of massless particles and pressure of quarks in photons is addressed. The special role of tensor polarization of spin-1 particles is analyzed. Special attention is payed to the role of EMT in coupling of quarks and gluons to gravity and manifestation of equivalence principle and its extensions. Interplay between hadronic and heavy-ion observables is also discussed.

Parallel 1 / **76**

Front-form approach to QED in an intense plane-wave field

Author: Sergey Bragin[1]

[1] *Max Planck Institute for Nuclear Physics*

Corresponding Author: s.bragin@mpi-hd.mpg.de

Recent development of the laser technologies for the production of extreme intensities has made high-power lasers a practical tool for studying subatomic world at the intensity frontier [1], complementary to the energy frontier. From the theoretical point of view, an intense laser field can be normally represented as a classical background plane-wave field. Because of the high intensity, the field must be taken into account nonperturbatively, which results, in particular, in the modifications of single-particle fermionic states with definite momentum and spin quantum numbers. These modifications reflect the momentum and spin dynamics of a particle inside the field and, due to the properties of the background field, can be consistently treated on the light cone, with the help of light-cone quantization and also a light-cone gamma-matrix basis [2]. In my presentation, I introduce the light-cone gamma-matrix basis and show how, combining with light-cone quantization, it allows to formulate QED in an intense plane-wave field in a complete front-form fashion. Furthermore, I demonstrate the approach with examples.

[1] A. Di Piazza et al. Extremely high-intensity laser interactions with fundamental quantum systems. Rev. Mod. Phys. 84, 1177 (2012). https://doi.org/10.1103/RevModPhys.84.1177

[2] S. Bragin. Front-form approach to quantum electrodynamics in an intense plane-wave field with an application to the vacuum polarization. Ph.D. thesis (2019). https://doi.org/10.11588/heidok.00026797

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Positronium structure: an illustration of nonperturbative renormalization in a basis light-front approach

Authors: Xingbo Zhao[1]; Kaiyu Fu[1]; Hengfei Zhao[1]; Yang Li[2]; James Vary[3]

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

[2] *USTC*

[3] *Iowa State University*

Corresponding Authors: xbzhao@impcas.ac.cn, jvary@iastate.edu, yanglee@mail.ustc.edu.cn, zhaohengfei950222@163.com, kaiyufu@impcas.ac.cn

We solve for the mass spectrum and structure of the positronium, the bound state formed by an electron and a positron, from the first-principles of QED. We adopt a nonperturbative approach based on light-front Hamiltonian formalism, named Basis Light-front Quantization. In this calculation we include the lowest two Fock sectors, $|e^+e^-\rangle$ and $|e^+e^-\gamma\rangle$, in the basis. We perform the nonperturbative fermion mass renormalization on the single-electron level. After solving the eigenvalue problem of the positronium, we obtain the mass spectrum and wave functions of the low-lying eigenstates, which are then compared with those obtained from a light-front one-photon-exchange effective interaction approach. Finally we present the probability of finding a photon in these low-lying states.

Parallel 2 / 78

Low x DIS at NLO in light-cone perturbation theory with massive quarks

Author: Risto S. Paatelainen[1]

Co-authors: Guillaume Beuf ; Tuomas Lappi [2]

[1] *CERN*

[2] *University of Jyvaskyla*

Corresponding Authors: tuomas.v.v.lappi@jyu.fi, guillaume.beuf@gmail.com, risto.sakari.paatelainen@cern.ch

Deep Inelastic Scattering (DIS) is the cleanest tool available to probe the content of a fast proton or nucleus. In the regime of low Bjorken x, one enters in the nonlinear regime of gluon saturation, where the gluons are better described as a strong coherent semi-classical field (a.k.a. Color Glass Condensate) than as a collection of quasi on-shell partons. Hence, that regime lies outside the validity range of the collinear factorization and is better described within the dipole factorization of DIS observables which allows to resum coherent multiple scattering on the target, and also to resum the high-energy leading logarithms (LL). One of the motivations to study in detail the regime of gluon saturation in proton and nuclei is that it drives the physics of the earliest stages of heavy collisions, leading to the formation of the Quark-Gluon Plasma.

So far, phenomenological studies have been performed successfully at LO with high energy leading log resummation in the dipole factorization using HERA data for proton DIS. However, in order to reach precision, NLO corrections should be included as well as high-energy NLL resummations. This

is important not only to extract as much knowledge as possible out of the HERA data, but also in prevision of future electron-proton and/or electron-nucleus colliders.

In this talk, we will present the first complete calculation of the (fixed order) NLO corrections to DIS structure functions on a dense target in the dipole factorization picture for the massive quark contribution (which is known to be sizable in DIS). The calculation is performed using light-cone perturbation theory.

Parallel 1 / 79

Poincaré invariant UV regularization on the light-front and mass renormalization

Author: Guillaume Beuf[None]

Co-authors: Risto Sakari Paatelainen [1]; Tuomas Lappi [2]

[1] *CERN*

[2] *University of Jyvaskyla*

Corresponding Authors: guillaume.beuf@gmail.com, risto.sakari.paatelainen@cern.ch, tuomas.v.v.lappi@jyu.fi

Mass renormalization for gauge theories in light-front perturbation theory (LFPT) has been a long-standing puzzle, leading to apparently inconsistant results in the literature. In this talk, I will show how to implement a fully Poincaré invariant UV regularization for LFPT calculations, like for example dimensional regularization. Within this approach, one obtains consistent and unambiguous results for mass renormalization at one loop. In particular, the mass correction for gauge bosons is now vanishing without the need for a counterterm. Moreover, the mass of charged or colored fermions is now renormalized in the same way in the numerator and in the denominator. The Poincaré invariant UV regularization should also have important consequences for the study of vacuum properties in LFPT.

Parallel 3 / 80

The QCD energy-momentum tensor for massive hadrons

Author: Sabrina Cotogno[1]

[1] *IPHT*

Corresponding Author: scotogno@nikhef.nl

We study the structure of the energy-momentum tensor (EMT) for massive hadrons of spin ≥ 1. When considering higher values for the spin of the particle, the number of form factors involved in the decomposition of the EMT local matrix element increases. The Lorentz generators, distinctive of each spin representation, can be used to arrange the structures appearing in the EMT parametrization and uniquely identify the terms which are independent of the spin of the particles and those which are present due to the spin, the latter related to spin multipoles.
Studying higher spins in this way allows us to better characterize the spin-universality of important hadronic relations, such as the Ji's sum rule, and develop the tools to construct the parametrization of the EMT for arbitrary spin.

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Hadron spectrum and Dyson-Schwinger equations

Author: Gernot Eichmann[1]

[1] *Tecnico Lisboa*

Corresponding Author: gernot.eichmann@tecnico.ulisboa.pt

I will review progress in calculating the properties of mesons, baryons and tetraquarks using Dyson-Schwinger and Bethe-Salpeter equations. This includes the spectrum of light and strange baryons and their transition form factors as well as states dominated by four-quark dynamics such as the X(3872) and other heavy-light tetraquark candidates. I will discuss recent advances in determining resonance properties using contour deformations, which can also serve as a tool for calculating hadron properties on the light front.

Parallel 1 / 82

Form factors and structure functions of heavy mesons and baryons

Author: Kamil Serafin[1]

[1] *University of Warsaw*

Corresponding Author: kamil.serafin@fuw.edu.pl

We present preliminary results for form factors and structure functions of some of spin-0, spin-1/2 and spin-1 heavy quarkonia and triply-heavy baryons in heavy flavor QCD. Using renormalization group procedure for effective particles (RGPEP) and gluon mass ansatz, approximate Hamiltonians for heavy quarkonia and triply-heavy baryons in QCD were found [1,2]. The approximate eigenfunctions of these Hamiltonians are used to obtain the results for form factors and structure functions. Charge radii that are calculated from the form factors are in the ballpark of expectations based on other theoretical results. The results for radii are in a surprisingly good agreement with lattice QCD results in cases where comparison is possible. The crudeness of approximations of the wave functions, however, presents a problem for calculations of magnetic properties of hadrons and for relativistic covariance of scattering amplitudes. To estimate corrections necessary to obtain reliable results for magnetic moments of spin-1/2 and spin-1 hadrons, we construct corrections to the wave functions using free quark spinors. These corrections approximately restore rotational covariance of the scattering amplitudes and allow us to give estimates of the magnetic moments. Magnetic moments of vector charmonia and bottomonia are in agreement with other theoretical results. Magnetic moments of B_c^* mesons and spin-1/2 ground states of bbc and ccb baryons are considerably larger than moments reported in the literature.

The hadron structure functions are computed in a simplified way, neglecting the huge difference between the scale of quark binding and the scale of the virtual photon in deep inelastic scattering (formally infinite). The calculations show interesting features, such as dependence of the structure function shape on the wave function nodes. However, these calculations can be considered merely a demonstration of potential utility of the method, because the transformation that connects effective particles at two different RGPEP scales, that of DIS and that of bound-state formation, is approximated by identity.

[1] Głazek, Gómez-Rocha, More, Serafin, Phys. Lett. B 773, 172 (2017)
[2] Serafin, Gómez-Rocha, More, Głazek, Eur. Phys. J. C 78, 964 (2018)

Parallel 1 / 83

Gauge boson mass as regulator of front-form dynamics

Author: Stanislaw D. Glazek[1]

[1] *University of Warsaw*

Corresponding Author: stglazek@fuw.edu.pl

Small-x divergences of a canonical Hamiltonian of Abelian gauge theory in the front form of quantum dynamics, are regulated using a mass parameter for gauge bosons, introduced through a mechanism analogous to the spontaneous breaking of global gauge symmetry [1]. The regularization includes addition of the third polarization state for massive vector bosons. A corresponding family of ultraviolet and infrared finite, scale-dependent renormalized Hamiltonians, is calculable order-by-order using the renormalization group procedure for effective particles (RGPEP). The RGPEP will be illustrated on two examples of second-order: the electron mass squared counter-term in QED and the resulting electron mass squared Hamiltonian term in a finite effective theory. Review of the orders of magnitude that characterize the scale-dependent dynamical mass effects order alpha in QED, given the current experimental upper limit on the photon mass, indicates the range of variables that need to be considered in resolving the front-form vacuum and zero-mode issues, related to results based on the dimensional regularization.
[1] S. D. Glazek, Acta Physica Polonica B 50, 5-26 (2019).

Plenary / 84

On the light-front wavefunctions and related observables of quarkonium states

Author: Maris Pieter[1]

[1] *Dept. of Physics and Astronomy, Iowa State University*

Corresponding Author: pmaris@iastate.edu

The light-front wavefunctions of hadrons allows us to calculate a wide range of physical observables; however, the wave-functions themselves cannot be measured. Furthermore, the light-front wavefunctions are typically expanded in their Fock components, and it is not clear, a priori, how many terms in this expansion are needed for quantitatively reliable calculations of hadron observables, and for restoration of rotational invariance. I will discuss recent approaches to calculate light-front wavefunctions of quarkonium and positronium which form ideal systems to investigate these questions. I will also discuss the prospects of extracting light-front observables such as distribution amplitudes and PDFs, and possibly even the light-front wavefunction, from other methods such as the explicitly covariant Bethe-Salpeter equation in ladder truncation, or from lattice QCD.

Parallel 3 / 85

Short-Range Structure of the Deuteron on the Light-Front

Author: Frank Vera[1]

Co-author: Misak Sargsian [1]

[1] *Florida International University*

Corresponding Authors: sargsian@fiu.edu, fvera002@fiu.edu

We study electro-disintegration of the deuteron at high momentum transfer aimed at describing its short-distance structure. Such studies are relevant for a number of phenomena related to high density nuclear matter, relativistic NN-interaction and at short distances nuclei structure in general. Due to the relativistic nature of the process, the theoretical framework is based on light-front approach, which allows a complete relativistic treatment of all components of the reaction, such as deuteron wave function, bound nucleon electromagnetic current, as well as final state interaction of fast struck nucleon with the spectator nucleon. The main advantage of the approach is that it allows effectively to account for the vacuum fluctuation contributions which are essential for processes that probe deuteron with large relative momentum of its nucleon constituents. We compare our calculations with the prediction of non-relativistic calculation as well as provide a preliminary comparisons with the experimental data being measured at Jefferson Lab.

Parallel 2 / **86**

Mean Field Quarks on the Light Front

Author: Christopher Leon[1]

Co-author: Misak Sargsian [1]

[1] *Florida International University*

Corresponding Author: cleon082@fiu.edu

We develop a non-perturbative, light-front approach for valence quark x-distribution in the nucleon to explain quark interactions in the mean field of the nucleonic interior. The main motivation for the model is to obtain a mean field description of the valence quarks as a baseline upon which to study the short-range quark-quark interactions that generate the high x tail of valence quark distributions. Our non-perturbative model is based on a residual system of the nucleon in which one assumes a factorization of the short-range valence quark and long-range dynamics. The nucleon structure functions are calculated using light-front dynamics and the effective Feynman diagrammatic approach is used to introduce valence quark and residual wave functions. The parameters of these wave functions are fixed by the position of the peak of $xfq(x)$ distribution of valence quarks at Q_0 corresponding to the charm-quark mass. With few parameters we achieved a very reasonable description of the up and down valence quark distributions in the moderate x region ($x \leq 0.5$) were one expects the mean field dynamics to dominate. The model however systematically underestimates the high x region where we expect enhanced contribution from partonic correlations.

Plenary / **87**

Double parton distributions of the pion in the NJL model

Authors: Wojciech Broniowski[1]; Enrique Ruiz Arriola[2]

[1] *IFJ PAN*

[2] *Universidad de Granada*

Corresponding Authors: earriola@ugr.es, wojciech.broniowski@ifj.edu.pl

We evaluate the quark double parton distribution (dPDF) function of the pion in the Nambu-Jona-Lasinio model, previously used to successfully obtain related quantities such as PDF, PDA, GPD,

TMD, etc. In this model the pion appears as a Goldstone boson of the spontaneously broken chiral symmetry and as a fully relativistic q qbar bound state of the Bethe-Salpeter equation. We show that at the quark model scale the model reproduces dPDF in the valon form, namely, constant times delta(1-x1-x2), where x1 and x2 are the longitudinal momentum fractions of the constituent quark and antiquark. Our analysis provides a nontrivial example of a dynamical calculation in a simple field-theoretic model, where all the required formal features are satisfied. In particular, the valon form satisfies the Gaunt-Stirling sum rules. Subsequent DGLAP evolution to higher momentum scales, achieved via Mellin moments, preserves these features. It results in a correlated partonic system, where the departure from the frequently used product ansatz is substantial.

Plenary / **88**

Review on heavy-ions@LHC and RHIC

Author: Barbara Antonina Trzeciak[1]

[1] *Utrecht University*

Corresponding Author: barbara.antonina.trzeciak@cern.ch

The main goal of heavy-ion programs of the LHC and RHIC experiments is to characterise properties of the hot and dense QCD matter, so called quark-gluon plasma, created in the heavy-ion collisions and the phase transition between the hadronic and the de-confined matter.
In this review, recent experimental results of relativistic heavy-ion collisions at the top RHIC and LHC energies and their connection with the light-front formalism will be discussed.

Plenary / **90**

The present and future science program at Jefferson Lab

Author: Jian-Wei Qiu[1]

[1] *Jefferson Lab*

Corresponding Author: jqiu@jlab.org

The CEBAF facility at Jefferson Lab (JLab) recently completed its 12 GeV upgrade, and is now capable of delivering high intensity electron beams to all four experimental halls simultaneously. It is now in its first full year operation and will produce incredibly amount of precision data to help address some critically important 21st century science questions, e.g., what is the role of gluonic excitations in the spectroscopy of light mesons? where is the missing spin in the nucleon - the role of quark/gluon orbital motion? can we reveal a novel quark/gluon landscape of nucleon? what is the relation between the partonic structure of nuclei and the nature of nuclear force? can we discover evidence for physics beyond the standard model in low energy precision measurements? In this talk, I will briefly summarize the current activities and the planned future science programs at JLab, and its role in leading to the future era of Electron-Ion Collider.

Plenary / **91**

Improved opacity expansion for medium-induced parton splitting

Author: Yacine Mehtar-Tani[None]

Improved opacity expansion for medium-induced parton splitting

Medium-induced parton splitting is the building block for jet evolution in the presence of a hot QCD medium and plays a central role in quantitative studies of jet quenching. It exhibits two regimes: single hard and multiple soft scattering regimes that dominate at high and low frequency respectively. A closed analytic formula encompassing both regimes is so far lacking. To remedy this we propose an improved opacity expansion approach where instead of expanding around vacuum the expansion is performed around the harmonic oscillator providing a better convergence of the series at low frequencies. We show that the first two orders account for the two known analytic limits.

Plenary / **92**

Overview of low-x experiments

Author: Radek Zlebcik[1]

[1] *Deutsches Elektronen-Synchrotron (DE)*

Corresponding Author: radek.zlebcik@cern.ch

The LHC and HERA experimental results are reviewed with focus on the low-x kinematic domain where the BFKL dynamics, saturation effects and the gluon transverse momentum play a role.
In particular, diffractive processes (involving J/psi, upsilon or jets), the central exclusive production in the hadron-hadron collisions and the forward jets produced in pp and pA are discussed.

Plenary / **93**

Parton distributions from light-front holographic QCD

Authors: Tianbo Liu[1]; Raza Sufian[2]; Guy de Teramond[3]; HansGunter Dosch[None]; Stanley Brodsky[4]; Alexandre Deur[1]

[1] *Jefferson Lab*

[2] *University of Kentucky*

[3] *UCR*

[4] *SLAC National Accelerator Laboratory*

Corresponding Authors: rssu222@uky.edu, sjbth@slac.stanford.edu, gdt@asterix.crnet.cr, liutb@jlab.org

Determining quark spin dependent distributions in the proton is a key task in hadron physics to understand strong interactions. Existing world data show positive polarization for up quarks and negative polarization for down quarks. However, perturbative QCD predicts maximally positive polarization for both up and down quarks at large longitudinal momentum limit, $x \to 1$, while extrapolations from global fits as well as many nucleon structure models favor a small negative polarization for down quarks at the limit. We present a new approach, motivated by the gauge/gravity correspondence and Veneziano duality, to study polarized quark distributions. Given the knowledge of unpolarized distributions, we have parameter-free determinations of corresponding polarized distributions, which are consistent with existing experimental data in the measured region and also with the perturbative QCD predictions at the large-x limit. Particularly, we predict the position where a sign change is expected for the polarization of down quarks. Our results will be tested very soon in upcoming experiments.

Plenary / **94**

Can we create quark-gluon plasma in small colliding systems?

Author: Maxime Guilbaud[1]

[1] *CERN*

Corresponding Author: m.guilbaud@cern.ch

Starting with the SPS and now RHIC and LHC, heavy-ion collisions (A-A) were used to study the quark-gluon plasma and its properties. Small colliding systems such as p-p and p-A were used as baseline to understand effects from vacuum QCD and cold nuclear effects respectively. Nevertheless since the discovery of quark-gluon plasma like signatures in small colliding systems (such as p-p, p-A, ...), a large amount of work was dedicated to understand their origin. Indeed, this new phenomena may imply that the current paradigms we have to describe A-A, p-A and p-p collisions need to be reconsidered. In this talk, an experimental overview of the current results and understanding will be given. A good control on our knowledge of the time-space evolution of high-energy hadronic collisions appears to be crucial. Along that line, some prospectives will be discussed.

Plenary / **95**

Small system physics and EIC

Author: Michael A. Winn[1]

[1] *Université Paris-Saclay (FR)*

Corresponding Author: michael.winn@cern.ch

Plenary / **96**

Overview of GPDs

Author: Paweł Sznajder[1]

[1] *National Centre for Nuclear Research*

Corresponding Author: pawel.sznajder@ncbj.gov.pl

Plenary / **97**

PDFs on the Lattice

Author: Fernanda Steffens[None]

Corresponding Author: fernanda.steffens@desy.de

Plenary / **98**

Overview of jet physics

Author: Gregory Soyez[1]

[1] *IPhT, CEA Saclay*

Corresponding Author: gregory.soyez@ipht.fr

Plenary / **99**

Early stages of heavy-ion collisions

Author: Francois Gelis[None]

Corresponding Author: francois.gelis@cern.ch

Heavy ion collisions pose interesting challenges to quantum chromodynamics, because they probe the parton structure of the incoming nuclei at very small longitudinal momentum fractions. Combined with the large size of nuclei, this may lead to the phenomenon of gluon saturation. The Color Glass Condensate is an effective QCD description that aims to cope with such a situation. In this talk, I will show how one may study heavy ion collisions in this framework.

Parallel 1 / **100**

Parton-pseudo distribution functions from Lattice QCD

Authors: Savvas Zafeiropoulos[1]; Kostas Orginos[2]; David Richards[3]; Alexander Rothkopf[4]; Joseph Karpie[5]; Balint Joo[6]; Anatoly Radyushkin[7]; Raza Sufian[6]

[1] *Universität Heidelberg*

[2] *William and Mary - Jlab*

[3] *Jefferson Lab*

[4] *University of Stavanger*

[5] *College of William and Mary*

[6] *JLAB*

[7] *ODU and JLAB*

Corresponding Authors: alexander.rothkopf@uis.no, s.zafeiropoulos@thphys.uni-heidelberg.de, jmkarpie@email.wm.edu, dgr@jlab.org, kostas@wm.edu

The light-cone definition of Parton Distribution Functions (PDFs) does not allow for a direct ab initio determination employing methods of Lattice QCD simulations that naturally take place in Euclidean spacetime. In this presentation we focus on pseudo-PDFs where the starting point is the equal time hadronic matrix element with the quark and anti-quark fields separated by a finite distance. We focus on Ioffe-time distributions, which are functions of the Ioffe-time ν, and can be understood as the Fourier transforms of parton distribution functions with respect to the momentum fraction variable x. We present lattice results for the case of the nucleon and the pion and we also perform a comparison with the pertinent phenomenological determinations.

Parallel 3 / **101**

Transverse Force Tomography

Author: Matthias Burkardt[1]

Co-authors: Fatma Aslan [1]; Marc Schlegel [1]

[1] *NMSU*

While twist-2 GPDs allow for a determination of the distribution of partons on the transverse plane, twist-3 GPDs contain quark-gluon correlations that provide information about the average transverse color Lorentz force acting on quarks. We demonstrate how twist-3 GPDs can be used to provide transverse position information about that force.

Parallel 3 / **102**

Dimuon experiments at the new COMPASS++/AMBER QCD facility at CERN

Author: Stephane Platchkov[1]

Co-author: on behalf of COMPASS++/AMBER Collaboration

[1] *CEA Saclay*

Corresponding Author: stephane.platchkov@cern.ch

The planned new fixed-target COMPASS++/AMBER QCD facility takes advantage of the uniqueness of the muon and hadron beams available at CERN. Its broad experimental programme aims at a deeper understanding of the strong interaction. After summarizing the main features of the facility, the present talk will focus on the Drell-Yan and charmonium production part of the programme. New high-statistics pion-induced data are expected to make a major contribution to the poorly known sea-quark distribution in the pion. In addition, comparison between light and heavy targets should shed new light on the EMC and energy loss effects.
On a longer term, the COMPASS++/AMBER facility will strongly benefit from the implementation of a new radio-frequency hadron beam separator, allowing for high-intensity kaon and antiproton beams. The talk will outline the physics opportunities offered by such an upgrade, namely on the kaon structure, which is experimentally unknown.

Plenary / **103**

Matching between equal-time and light-front quantization in non-perturbative calculations

Author: Matthew Thomas Walters[1]

[1] *CERN*

Corresponding Author: matthew.walters@cern.ch

Parallel 1 / **104**

Timelike Compton Scattering with CLAS12 at Jefferson Lab

Author: Pierre Chatagnon[1]

[1] *IPN Orsay*

Corresponding Author: chatagnon@ipno.in2p3.fr

Generalized Parton Distributions (GPDs) describe correlations between the longitudinal momentum and the transverse position of the partons inside the nucleon . GPDs have been studied in many experiments worldwide mainly using Deeply Virtual Compton Scattering (DVCS, ep $\rightarrow$ e'p'γ).

This talk will highlight the measurement of the time-reversal conjugate process of DVCS, Timelike Compton Scattering (TCS). TCS on the proton (γp $\rightarrow$ γ^*p'$\rightarrow$ e^+e-p') is the photoproduction of a virtual timelike photon, which then decays into a lepton pair. Experimental studies of DVCS and TCS are complementary. Indeed, beam and target spin asymmetries for DVCS give direct access to the imaginary part of combinations of Compton Form Factors (CFFs, which are related to GPDs), whereas the angular asymmetries of the decay lepton pairs in TCS allow to access primarily the real parts of CFFs. The experimental measurement of the TCS angular asymmetry will provide new information on the real part of GPDs, which is less constrained by existing DVCS data than the imaginary part.

The upgraded CEBAF accelerator and the recently constructed CLAS12 detector of Jefferson Lab provide the ideal setting to perform a TCS experiment CLAS12 took data with a 10.6 GeV electron beam impinging on a liquid-hydrogen target in the spring and fall of 2018. This talk will assess the current status of the analysis of CLAS12 data and present preliminary results for TCS.

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Welcome

Author: Cédric Lorcé[1]

[1] *Ecole polytechnique*

Corresponding Author: cedric.lorce@polytechnique.edu

Parallel 3 / 107

Glueballs as gravitons in holographic approaches

Corresponding Author: matteo.rinaldi@pg.infn.it

Parallel 3 / 108

Break

Parallel 3 / 109

Break

Parallel 3 / 110

Break

Parallel 1 / **111**

Break

Parallel 3 / **112**

Break

Special session / **113**

Much ado about nothing - an introduction to the LF vacuum

Corresponding Author: burkardt@nmsu.edu

Special session / **114**

Structure of light front vacuum sector

Corresponding Author: philip.mannheim@uconn.edu

Special session / **115**

The Delta Functions in PDFs and the QCD Vacuum Structure

Special session / **116**

Non-perturbative aspects of light-front quantisation

Corresponding Author: peter.lowdon@polytechnique.edu

Special session / **117**

Ward-Takahashi Identity on the Light Front

Corresponding Author: jpachecodm@gmail.com

Special session / **118**

Role of Light-Front Zero Modes in String Theory

Corresponding Author: daya.kulsh@gmail.com

Special session / **119**

Zero-mode manifestation in the quantum tunneling in the light front

Corresponding Author: asuzuki@lasierra.edu

Special session / **120**

Discussion

Parallel 2 / **121**

Conformal invariance of TMD rapidity evolution

Author: Giovanni A. Chirilli[1]

[1] *University of Regensburg*

Corresponding Author: giovanni.chirilli@gmail.com

The most known scheme to regulate the rapidity/UV divergences of the Transverse Momentum Distribution operators due to the infinite light-like gauge links is the Collis Soper Sterman formalism or the Soft Collinear Effective Theory formalism. An alternative choice is provided by the scheme used in the small-x physics. The corresponding evolution equations differ already at leading order. In view of the future Electron Ion Collider accelerator, which will probe the TMDs at values of the Bjorken x in the region between small-x to x˜1, the different formalisms need to be reconciled. I will discuss the conformal properties of TMD operators and present the result of the conformal rapidity evolution of TMD operators in the Sudakov region.

Parallel 1 / **122**

Break

Parallel 3 / **123**

Break

Parallel 1 / 124

Quantum Tunneling Time in the Light Front

Corresponding Author: asuzuki@lasierra.edu