Diffraction and Low-x 2022

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Corigliano Calabro, Italy

Book of Abstracts

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The LHCspin project

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The goal of LHCspin is to develop, in the next few years, innovative solutions and cutting-edge technologies to access spin physics in high-energy polarized fixed-target collisions, by exploring a unique kinematic regime given by the LHC beam and by exploiting new probes.
This ambitious task poses its basis on the recent installation of SMOG2, the unpolarized gas target in front of the LHCb spectrometer. Specifically, the unpolarized target, already itself a unique project, will allow to carefully study the dynamics of the beam-target system, and clarify the potentiality of the entire system, as the basis for an innovative physics program at the LHC.
The forward geometry of the LHCb spectrometer (2<□<5) is perfectly suited for the reconstruction of particles produced in fixed-target collisions. This configuration, with center-of-mass energies ranging from 115 GeV in pp interactions to 72 GeV in collisions with nuclear beams, allows to cover a wide backward rapidity region, including the poorly explored high x-Bjorken and high x-Feynman regimes. With the instrumentation of the proposed target system, LHCb will become the first experiment delivering simultaneously unpolarized beam-beam collisions at √s=14 TeV and both polarized and unpolarized beam-target collisions.
The status of the project is presented along with a selection of physics opportunities.

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Discussion: ep and e-ion physics

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Far-Forward detectors at the Electron-Ion Collider

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The Electron-ion Collider to be constructed at Brookhaven National Lab is considered to be the next generation “dream machine” in future nuclear physics research. Extending the acceptance of the detector to the far forward region ($\eta > 4$) is extremely important for a wide range of measurements to be performed at EIC. The designs of the far-forward detectors (B0-spectrometer and electromagnetic calorimeter, Roman Pot and Off-Momentum dectectors and the Zero-Degree Calorimeter) proposed by the ECCE Consortium are described. Detection of forward-going particles with high energy and position resolution as well as two-photon separation reveal new possibilities to provide experimental access to various processes including pion form factor measurements, diffractive and photoproduction processes and u-channel DVCS. The prospects of such measurements exploiting, in particular the B0 and ZDC detectors, are also discussed.

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Electron-Ion Collisions at the LHeC and FCC-eh

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The LHeC and the FCC-eh will open a new realm in our understanding of nuclear structure and the dynamics in processes involving nuclei, in an unexplored kinematic domain. In this talk we will review the most recent studies as shown in the update of the 2012 CDR [1]. We will discuss the determination of nuclear parton densities in the framework of global fits and for a single nucleus. Then we will discuss diffraction, both inclusive and exclusive. Finally we will demonstrate the unique capability of these high-energy colliders for proving the long sought non-linear regime of QCD, saturation, to exist (or to disprove). This is enabled through the simultaneous measurements, of similar high precision and range, of ep and eA collisions which will eventually disentangle non-linear parton-parton interactions from nuclear environment effects.

[1] LHeC Collaboration and FCC-he Study Group, P. Agostini et al., e-Print: 2007.14491 [hep-ex].

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Detectors and physics at the Electron-Ion Collider

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Azimuthal correlations in photoproduction and deep inelastic ep scattering at HERA

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On behalf of the ZEUS Collaboration.
JHEP 12 (2021) 102

Collective behaviour of final-state hadrons, and multiparton interactions are studied in high-multiplicity ep scattering at a centre-of-mass energy sqrt(s) = 318GeV with the ZEUS detector at HERA. Two- and four-particle azimuthal correlations, as well as multiplicity, transverse momentum, and pseudorapidity distributions for charged-particle multiplicities N_(ch) >= 20 are measured. The dependence of two-particle correlations on the virtuality of the exchanged photon shows a clear transition from photoproduction to neutral current deep inelastic scattering. For the multiplicities studied, neither the measurements in photoproduction processes nor those in neutral current deep inelastic scattering indicate significant collective behaviour of the kind observed in high-multiplicity hadronic collisions at RHIC and the LHC. Comparisons of PYTHIA predictions with the measurements in photoproduction strongly indicate the presence of multiparton interactions from hadronic fluctuations of the exchanged photon.

Discussion: Low x, PDFs, hadronic final state / **87**

The parton distributions at small momentum fractions

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When parton momentum faction 𝑥 of hadron becomes small, an enhancement from small-𝑥 logarithms shows up, and eventually, we enter into a partonic saturation region. A consistent treatment of the small-𝑥 logarithms requires an all-order resummation which can be achieved with the BFKL formalism. However, a boundary to delineate the small-𝑥 resummation region from saturation one is ambiguous. In this study, we take a 𝑥-dependent DIS scale motivated by the saturation model in a global analysis, which improves the QCD description of the HERA DIS data. In parallel, we also explore the BFKL improved DGLAP evolution, which achieves a similar 𝜒2 for the same data set. We compare various impacts of these two methods on the parton distributions, and also phenomenological implications, including Drell-Yan or Higgs boson production at future hadron colliders (FCC), the ultra-high-energy neutrino-nucleus scattering, and structure function measurements at future electron-hadron colliders (LHeC/FCC-eh).

Discussion: Low x, PDFs, hadronic final state / **85**

Theoretical, parametrization, and sampling uncertainties in parton distributions: a view from CT

Author: Pavel Nadolsky[1]

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I summarize recent studies of various types of uncertainties in the global analysis of parton distribution functions (PDFs) by the CTEQ-TEA group. Sampling of the multivariate PDF parameter space introduces an important source of uncertainty that has implications for critical collider applications such as W boson mass measurement and Higgs physics. Parametrization and sampling uncertainties can be at least as prominent as (N)NNLO theoretical uncertainties in both the Hessian and Neural Network PDF frameworks. To test if the sampling of the PDF uncertainty of an experimental observable is truly representative of all acceptable solutions, we introduce a technique ("a hopscotch scan") based on a combination of parameter scans and stochastic sampling. With this technique, we demonstrate that CT, MSHT, and NNPDF fits arrive at different estimates of PDF uncertainties when fitting similar experimental data, and we elucidate a source of this difference.

Discussion: Low x, PDFs, hadronic final state / **80**

News from MSHT

Author: Lucian Harland-Lang[1]

[1] *University of Oxford*

The latest developments from MSHT including N3LO predictions, which have strong impact at low-x, will be reviewed.

Discussion: Photon-photon physics and hard diffraction / **93**

Modelling semi-exclusive particle production at the LHC

Author: Lucian Harland-Lang[1]

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In this talk we will present the results of a new calculation of semi-exclusive photon-initiated production, that is either with intact outgoing protons or rapidity gaps present in the final state, and with no colour flow between the colliding LHC protons. This accounts for both the possibility of proton dissociation and the survival factor probability of no additional proton-proton interactions, including its kinematic and process dependence. Our calculation is provided in the publicly available SuperChic 4 Monte Carlo (MC) generator, and can be passed to a general purpose MC for showering and hadronization of the final state.

Discussion: Photon-photon physics and hard diffraction / 91

gamma-UPC: Automated generation of exclusive photon-photon processes in ultraperipheral proton and nuclear collisions

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[2] *Centre National de la Recherche Scientifique (FR)*

The automated generation of arbitrary exclusive final states produced via photon fusion in ultraperipheral high-energy collisions of protons and/or nuclei is implemented in the MadGraph5_aMC@NLO and HelacOnia Monte Carlo codes. Cross sections are calculated in the equivalent photon approximation using γ fluxes derived from electric dipole and charge form factors, and incorporating hadronic survival probabilities. Multiple examples of $\gamma\gamma$ cross sections computed with this setup, named gamma-UPC, are shown for proton-proton, proton-nucleus, and nucleus-nucleus ultraperipheral collisions (UPCs) at the Large Hadron Collider and Future Circular Collider. Total photon-fusion cross sections for the exclusive production of spin-0,2 resonances (quarkonium, ditauonium, and Higgs boson; as well as axions and gravitons), and for pairs of particles ($J/\psi J/\psi$, WW, ZZ, $Z\gamma$, $t\bar{t}$, HH) are presented. Differential cross sections for exclusive dileptons and light-by-light scattering are compared to LHC data. This development paves the way for the upcoming automatic event generation of any UPC final state with electroweak corrections at next-to-leading-order accuracy and beyond.

Discussion: Recent theoretical results on QCD and saturation / 59

BFKL as a multiperipheral model in multiparticle production and its conformal spin dependence in hard diffraction

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Firstly, we will discuss the multipherical structure of BFKL final states.
Secondly,the conformal spin dependence of the perturbative QCD vacuum singularity will be shown in detail.

Joint session: Recent theoretical results on QCD and saturation + low x, PDFs and hadronic final state / 132

Discussion session: High-energy QCD and resummations

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Joint session: Recent theoretical results on QCD and saturation + low x, PDFs and hadronic final state / **47**

BSM and SM signals and backgrounds in Far-Forward Experiments at the LHC

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Two far-forward experiments are currently taking data during Run 3 at the Large Hadron Collider (LHC): FASERnu [1] and SND@LHC [2]. They are sensitive to some classes of BSM particles, muons and neutrinos produced in the ATLAS interaction point (IP) and propagating for several hundred meters along the tangent to the accelerator beamline, up to two caverns located in opposite directions with respect to the IP, respectively. Proposals are being prepared to extend these experiments to bigger ones during the HL-LHC phase. One of the possibilities under discussion is to build a Forward Physics Facility (FPF) capable of hosting a number of different far-forward experiments. In this talk I will discuss BSM and SM signals and backgrounds at the FPF, using as a basis two extended papers produced so far on the topic [3,4] to which various participants e/o conveners of this Workshop have contributed, plus other ones closely related, and further work in progress. I will also sketch the possibility for alternatives and complementary experiments. I will mainly focus on QCD-related aspects, considering the main interests of the audience of this Workshop.

[1] FASER Collaboration, "Technical Proposal: FASERnu", [arXiv:2001.03073].

[2] SHIP Collaboration, "SND@LHC", [arXiv:2002.08722].

[3] L.A. Anchordoqui et al. "The Forward Physics Facility: Sites, experiments and physics potential", Phys. Rept. 968 (2022), 1-50 [arXiv:2109.10905].

[4] J.L. Feng et al. "The Forward Physics Facility at the High-Luminosity LHC", to be published in Journal of Physics G: Nuclear and Particle Physics [arXiv:2203.05090].

Joint session: Recent theoretical results on QCD and saturation + low x, PDFs and hadronic final state / **72**

Quarkonium inclusive production: negative NLO cross sections, scale fixing and high-energy resummation

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We address the issue of negative total cross sections for inclusive hadroproduction of pseudoscalar quarkonia (η_Q) and photoproduction of vector quarkonia (ψ, Υ) at increasing energies in NLO collinear-factorisation computations in the $\overline{MS}$ scheme. We discuss two solutions:

- fixing the factorisation scale to avoid an over-subtraction of the collinear contributions by the Altarelli-Parisi counter terms at large partonic energies;
- resumming $\ln(1/z)$ contributions through high-energy factorisation with a new matching to collinear factorisation at finite z.

In both cases, we discuss the corresponding phenomenology at different energies including a detailed assessment of the theoretical uncertainties.

References:

- J.P. Lansberg, M. Nefedov and M.A. Ozcelik, *Matching next-to-leading-order and high-energy-resummed calculations of heavy-quarkonium-hadroproduction cross sections*, JHEP **05** (2022), 083
- A. Colpani Serri, Y. Feng, C. Flore, J.P. Lansberg, M.A. Ozcelik, H.S. Shao and Y. Yedelkina, *Revisiting NLO QCD corrections to total inclusive J/ψ and Υ photoproduction cross sections in lepton-proton collisions*, [arXiv:2112.05060 [hep-ph]].
- J.P. Lansberg and M.A. Ozcelik, *Curing the unphysical behaviour of NLO quarkonium production at the LHC and its relevance to constrain the gluon PDF at low scales*, Eur. Phys. J. C **81** (2021) no.6, 497 [arXiv:2012.00702 [hep-ph]].

Joint session: Recent theoretical results on QCD and saturation + low x, PDFs and hadronic final state / **75**

Higher-order fiducial distributions within the transverse momentum resummation formalism.

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We present high-accuracy QCD predictions for the transverse-momentum (qT) distribution and fiducial cross sections of Drell-Yan lepton pairs produced in hadronic collisions. At small values of qT we resum to all perturbative orders the logarithmically enhanced contributions up to next-to-next-to-next-to-leading logarithmic (N3LL) accuracy, including all the next-to-next-to-next-to-leading order (N3LO) terms. Our resummed calculation has been implemented in the public numerical program DYTurbo, which produces fast and precise predictions with the full dependence on the final-state lepton kinematics. We consistently combine our resummed results with the known O(aS^3) fixed-order predictions at large values of qT obtaining full N3LO accuracy for fiducial cross sections. We show numerical results for Z production at LHC energies discussing the reduction of the perturbative uncertainty with respect to lower-order calculations.

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A parton branching algorithm with transverse momentum dependent splitting functions

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Parton branching methods underlie the Monte Carlo (MC) generators, being therefore of key importance for obtaining high energy physics predictions.
We construct a new parton branching algorithm which for the first time incorporates the off-shell, transverse-momentum dependent (TMD) splitting functions, defined from the high-energy limit of partonic decay amplitudes.
Based on these TMD splitting functions we construct a new TMD Sudakov form factor.
We present the first MC implementation of the algorithm for the evolution of the TMD and integrated parton distribution functions (PDFs). We use this implementation to evaluate small-x corrections to the distributions and to verify the momentum sum rule.
Presented study is a first step towards a full TMD MC generator covering the small-x phase space.

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The next-to-leading order Higgs impact factor in the infinite top-mass limit

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We present a full NLO result for the forward Higgs boson impact factor, obtained in the infinite top-mass limit. We discuss problems associated with a high-energy computation in the presence of the Higgs-gluons effective vertex.
This impact factor is a key ingredient to describe the inclusive hadroproduction of a forward Higgs in the limit of small Bjorken x, as well to study inclusive forward emissions of a Higgs boson in association with a backward identified object.
Lastly, a possible extension of this calculation to the case of Higgs impact factor via gluon fusion in the central-rapidity region, is also discussed.

Joint session: Recent theoretical results on QCD and saturation + low x, PDFs and hadronic final state / 78

Soft and next-to-soft resummation for QCD observables

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In this talk, I will disucss a framework to resum soft and next-to-soft enhanced logarithms to all orders in perturbative QCD. These large logarithms are comprises of distributions log^i (1−z)/(1−z) resulting from soft plus virtual (SV) and logarithms of the kind log^i(1−z) from next to SV (NSV) contributions. We use collinear factorisation and renormalisation group invariance as the building blocks to achieve this. Using this framwork we study the numerical implications of NSV corrections in the context of Drell-Yan process and Higgs boson productions at LHC. The talk is based on the works : Phys.Rev.D 105 (2022) 9, 094035, Eur.Phys.J.C 82 (2022) 3, 234, Phys.Rev.D 105 (2022) 9, L091503.

Joint session: Recent theoretical results on QCD and saturation + low x, PDFs and hadronic final state / 86

Direct-space pT resummation and the N3LO Drell-Yan cross section

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I describe resummation of colour-singlet transverse momentum and related observables in momentum space, as well as ensuing recent fiducial predictions in Drell Yan at third order in perturbation theory.

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Stabilizing BFKL via heavy-flavor and NRQCD fragmentation

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It is widely recognized that high-energy calculations performed via the NLL BFKL resummation of energy logarithms suffer from strong instabilities that become manifest when renormalization and factorization scales are varied from their *natural* values, namely the ones dictated by kinematics. In the case of observables featuring light-particle emissions, such as Muller–Navelet and light-hadron plus jet correlations, these instabilities are so strong to hamper any possibility to perform precision studies at natural scales. We provide evidence that LHC final states sensitive to heavy-flavored hadrons exhibit a fair and solid stability of these observables under higher-order corrections and scale variations. The stabilization mechanism is encoded in the peculiar behavior of the gluon collinear fragmentation function (FF) describing the heavy hadron. It comes out as is an *intrinsic* that becomes manifest whenever a species with heavy flavor is detected. This remarkable property, called *natural stability* of the high-energy resummation, emerges both in the case of a single-charmed or single-bottomed hadron emission, depicted by means of a heavy-flavor FF parametrization fitted to data, and also when a vector quarkonium state or a charmed B-meson is described in term of a DGLAP-evolving NRQCD FF set.

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Next-to-Leading Order virtual correction to the Higgs-induced DIS

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We calculate the Next-to-Leading Order (NLO) virtual correction to the Higgs-induced DIS in the infinite top mass limit. Since we want to use this result in the framework of k_t-factorization to resum small-x logarithms up to Next-to-Leading-Logarithm (NLL), we work in light-cone gauge and we keep the incoming gluon off-shell. This choice raises many challenging points like the presence of spurious singularities and a different definition of the counter terms. We address these points by giving a method to compute integrals with spurious gauge singularities and by calculating the counter term for the effective vertex. This calculation is a necessary ingredient for the impact factor that will be used to resum up to NLL small-x logarithms for this process.

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QCD at a Forward Physics Facility at the High-Luminosity LHC

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The Forward Physics Facility (FPF) is a proposal to enlarge an existing cavern in the far-forward region of ATLAS to house a suite of experiments with groundbreaking new capabilities for many Standard Model studies and new physics searches. Although existing LHC detectors have great coverage of the central region, the production of particles in the far-forward direction is poorly constrained. In this regime, the measurement of the neutrino flux and spectrum will provide constraints on QCD that are complementary to those provided by other facilities. This will help validate and improve the underlying hadronic interaction models and multi-purpose event generators, help constrain the gluon PDF in the low x region.

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Stabilizing BFKL via heavy-flavor and NRQCD fragmentation

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Measurement of the cross-section ratio sigma(psi(2S))/sigma(J/psi(1S)) in exclusive photoproduction at HERA

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On behalf of the ZEUS Collaboration.
Submitted to JHEP.

The exclusive photoproduction reactions gamm p -> J/psi(1S) p and gamma p -> psi(2S) p have been measured at an ep centre-of-mass energy of 318 GeV with the ZEUS detector at HERA using an integrated luminosity of 373 pb-1. The measurement was made in the kinematic range 30 < W < 180 GeV, Q^2 < 1 GeV^2 and |t| < 1 GeV^2, where W is the photon–proton centre-of-mass energy, Q^2 is the photon virtuality and t is the squared four-momentum transfer at the proton vertex. The decay channels used were J/psi(1S) -> mu+mu−, psi(2S) -> mu+mu− and psi(2S) -> J/psi(1S)pi+pi− with subsequent decay J/psi(1S) -> mu+mu−. The ratio of the production cross sections, R = sigma(psi(2S))/sigma(J/psi(1S)), has been measured as a function of W and |t| and compared to previous data in photoproduction and deep inelastic scattering and with predictions of QCD-inspired models of exclusive vector-meson production, which are in reasonable agreement with the data.

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New developments in N=2 supersymmetric gauge theories: integrability, black holes

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In this talk I'll explain how new physical results in 4D (N=2) supersymmetric matter gauge theories can be found by connecting them to 2D quantum integrable models. In particular, we set up an identification between the basic mathematical and physical objects of the two kind of theories (the Q, Y and T functions of integrability and the periods and masses of the gauge theories) and from this a flow of concepts and mathematical identities between them is derived. Also, we use such new correspondence to prove another very recently found correspondence between precisely the same kind of gauge theories and black holes perturbation theory. From this several new insights into black holes theory follow, especially a new powerful way of computing quasinormal modes frequencies (the Thermodynamic Bethe Ansatz nonlinear integral equation), characterising the gravitational wave signal (in the ringdown phase of black hole merging). We do this in all details for SU(2) gauge theories with Nf=0,1,2 flavours.

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Single, double and central diffractive dissociation of protons at high energies

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Single, double and central diffractive dissociation of protons is studied at high energies in a Regge-pole model. The main premises are: 1) Regge factorization, 2) inelastic vertices identified with DIS SFs, 3) Duality relation between high- and low missing masses, 4) Non-linear, complex Regge trajectories, updated.
The new results concern: 1) the dip-bump structure in the differential cross sections of single diffraction; 2) angular distribution of particles resulting from the decay of diffractively produced resonance. Within the model we analyze the existing and future LHC data, including the widths of produced resonances, including glueballs and those containing heavy quarks.

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Pseudo- and quasi-PDFs in the BFKL approximation

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o calculate the PDFs from first principles in Lattice gauge theories it is convenient to considerthe Ioffe-time distribution defined through gauge-invariant bi-local operators with spacelike separa-tion. Lattice calculations provide values for a limited range of the distance separating the bi-localoperators. In order to perform the Fourier transform and obtain the pseudo- and the quasi-PDFs,it is then necessary to extrapolate the large-distance behavior.I will discuss the formalism one may use to study the behavior of the Ioffe-time distribution atlarge distances and show that the pseudo-PDF and quasi-PDF are very different at this regime.Using light-ray operators, I will also show that the higher twist corrections of the quasi-PDF come in not as inverse powers of Pbut as inverse powers of xBP.

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Higher-point functions in N=4 SYM from an integrable system

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We review the computation of anomalous dimensions in planar N=4 super Yang-Mills theory from an integrable system, i.e. AdS_5/CFT_4 ''integrability". We then introduce the hexagon operator originally designed by Basso, Komatsu, and Vieira for three-point functions. It is argued that four- and higher-point functions can be studied using hexagon tessellations. A ''gluing prescription" for the elementary tiles leads to
sum-integrals akin to the MB representation. We comment on the status quo,
open problems, and research directions.

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BFKL factorizations for Mueller-Tang jets at LHC in NLLA

Corresponding Authors: colferai@fi.infn.it, dimitri.colferai@unifi.it

I present prediction for cross section of Mueller-Tang jets (jet-gap-jet) processes at LHC, obtained by using the BFKL approach, where both impact factors and gluon Green functions are calculated in the next-to-leading logarithmic approximation (NLLA). I discuss also the issue of the validity of the standard BFKL factorization for such processes, and show that the actual violation is small, and the present results provide a reliable computation of the cross section.

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Discussion session: PDFs

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Low x, PDFs and hadronic final states / **17**

Measurement and QCD analysis of inclusive jet production in deep inelastic scattering at HERA

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On behalf of the ZEUS Collaboration.

A new measurement of inclusive jet cross sections in neutral current deep inelastic scattering using the ZEUS detector at the HERA collider is obtained. The data were taken at HERA2 at a center of mass energy of 318 GeV and correspond to an integrated luminosity of 347 pb-1. Massless jets, reconstructed using the k_T-algorithm in the Breit reference frame, are measured as a function of the squared momentum transfer Q^2 and the transverse momentum of the jets in the Breit frame p_T,Breit. The measured jet cross sections are compared to previous measurements as well as NNLO QCD theory predictions. The measurement is used in a QCD analysis at NNLO accuracy to perform a simultaneous determination of parton distribution functions of the proton and the strong coupling constant, resulting in a value of alpha_s(MZ^2) = 0.1138 +- 0.0014 (exp/fit) +0.0004 −0.0008 (model/param.) +0.0008 −0.0007 (scale). A significantly improved accuracy is observed compared to similar measurements of the strong coupling constant.

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Probing low-x phenomena at LHCb

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The LHCb detector is able to probe kinematic coverage at low Bjorken-x down to 1e-5 or lower due to its forward rapidity coverage. In this talk, studies of vector boson and hadron production in proton-proton and proton-lead collisions are presented. The Z boson events are used to probe the proton structure while a relatively unknown low-x region is studied with charged and neutral hadron production. Comparisons to theoretical model calculations are also discussed.

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Impact of jet-production data on the next-to-next-to-leading-order determination of HERAPDF2.0 parton distributions

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On behalf of the H1 and ZEUS Collaborations.
Eur. Phys. J. C82 (2022) 243

The HERAPDF2.0 ensemble of parton distribution functions (PDFs) was introduced in2015. The final stage is presented, a next-to-next-to-leading-order (NNLO) analysis of theHERA data on inclusive deep inelasticepscattering together with jet data as published bythe H1 and ZEUS collaborations. A perturbative QCD fit, simultaneously ofαs(M2Z) andand the PDFs, was performed with the resultαs(M2Z)=0.1156±0.0011 (exp)+0.0001−0.0002(model+parameterisation)±0.0029 (scale). The PDF sets of HERAPDF2.0Jets NNLO were de-termined with separate fits using two fixed values ofαs(M2Z),αs(M2Z)=0.1155 and 0.118,since the latter value was already chosen for the published HERAPDF2.0 NNLO analysisbased on HERA inclusive DIS data only. The different sets of PDFs are presented, evalu-ated and compared. The consistency of the PDFs determined with and without the jet datademonstrates the consistency of HERA inclusive and jet-production cross-section data. Theinclusion of the jet data reduced the uncertainty on the gluon PDF. Predictions based on thePDFs of HERAPDF2.0Jets NNLO give an excellent description of the jet-production dataused as input.

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Jets separated by a large pseudorapidity gap at the Tevatron and at the LHC

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We present a phenomenological analysis of events with two high transverse momentum jets separated by a large (pseudo-)rapidity interval void of particle activity, also known as jet-gap-jet events. In the limit where the collision energy is much larger than any other momentum scale, the jet-gap-jet process is described in terms of perturbative pomeron exchange between partons within the Balitsky–Fadin–Kuraev–Lipatov (BFKL) limit of perturbative quantum chromodynamics (QCD). The BFKL pomeron exchange amplitudes, with resummation at the next-to-leading logarithmic approximation, have been embedded in the PYTHIA8 Monte Carlo event generator. Standard QCD dijet events are simulated at next-to-leading order in αs\alpha_sαs matched to parton showers with POWHEG+PYTHIA8. We compare our calculations to measurements by the CDF, D0, and CMS experiments at center-of-mass energies of 1.8, 7 and 13 TeV. The impact of the theoretical scales, the parton densities, final- and initial-state radiation effects, multiple parton interactions, and p_T thresholds and multiplicities of the particles in the rapidity gap on the jet-gap-jet signature is studied in detail. With a strict gap definition (no particle allowed in the gap), the shapes of most distributions are well described except for the CMS azimuthal-angle distribution at 13 TeV.

Low x, PDFs and hadronic final states / **24**

Helix string fragmentation and charged particle correlations with ATLAS

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Correlations between charged particles provide important insight about hadronization process. The analysis of the momentum difference between charged hadrons in pp, p-lead, and lead-lead collisions

of various energies is performed in order to study the dynamics of hadron formation. The spectra of correlated hadron chains are explored and compared to the predictions based on the quantized fragmentation of a three dimensional QCD helix string. This provides an alternative view of the two-particle correlation phenomenon typically attributed to the Bose-Einstein correlation, which will also be presented.

Low x, PDFs and hadronic final states / 4

Measurement of mass dependence of the transverse momentum of lepton pairs in Drell-Yan production in proton-proton collisions at sqrt{s} = 13 TeV

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The double differential cross sections of the Drell–Yan lepton pair ($\ell^+\ell^-$, dielectron or dimuon) production, as functions the invariant mass $m_{\ell\ell}$, transverse momentum $p_{\mathrm{T}}(\ell\ell)$, and
φ^*, are measured. The φ^* observable is highly correlated with
$p_{\mathrm{T}}(\ell\ell)$ and is used to probe the low-$p_{\mathrm{T}}(\ell\ell)$
region in a complementary way. Dilepton masses up to 1\TeV are investigated. Additionally, a measurement is performed requiring at least one jet in the final state. To benefit from partial cancellation of the systematic uncertainty, the ratios of the differential cross sections in $p_{\mathrm{T}}(\ell\ell)$ and φ^* for different $m_{\ell\ell}$ ranges over the ones in the \PZ mass peak interval are presented. The collected data correspond to an integrated luminosity of $36.3\,\mathrm{fb}^{-1}$ of proton–proton collisions recorded with the CMS detector at the LHC at a center-of-mass energy of 13\TeV in 2016. Measurements are compared to state-of-the-art predictions based on perturbative quantum chromodynamics, including soft-gluon resummation.

Low x, PDFs and hadronic final states / 120

Discussion seesion: PDFs, Low x

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Low x, PDFs and hadronic final states / 48

An interplay of small- and large-x effects in the QCD predictions for prompt atmospheric neutrino flux at IceCube

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The predictions for the atmospheric neutrino flux at high energies strongly depend on the contribution of prompt neutrinos, which are determined by the production of charmed mesons in the atmosphere at extremely high energies and very forward rapidities. Study of charm production in the far-forward directions requires to deal with a very asymmetric kinematics configuration with extremelly small-x on one side and very large-x on the other. Therefore model predictions for charm cross section known as the state of the art for midrapidity regions have to be supplemented here by dedicated small- and large-x effects. In this talk I will present our estimations of the related cross sections, recently obtained and discussed taking into account the presence of an intrinsic charm (IC) component in the proton wave function at large-x and the QCD dynamics modified by the onset of

saturation effects at small-x. In this study the impact on the predictions for the prompt neutrino flux is investigated assuming different values for the probability to find the IC in the nucleon (Pic). We demonstrate that for Pic ~ 1%, the IC component dominates the high-energy prompt neutrino flux. A first comparison with the IceCube data is performed and upper limits on the amount of IC are obtained for the linear and nonlinear descriptions of the QCD dynamics.

[1.] V.P. Goncalves, R. Maciula and A. Szczurek,
"Impact of intrinsic charm amount in the nucleon and saturation effects on the prompt atmospheric ν_μ flux for IceCube",
Eur. Phys.J. C82, no.3, 236 (2022)

Low x, PDFs and hadronic final states / **69**

Small-x resummation in coeffcient function for differential heavy-quarks production and next-to-leading logarithms

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Precise theoretical predictions of QCD scattering and radiation processes are fundamental building blocks for the LHC precision program. Fixed-order computations must be supplemented by all-order resummations where logarithmically-enhanced contributions become large. Among those, small-x logarithms are enhanced when the ratio, $x = \frac{Q^2}{S}$ between the typical energy scale of a scattering process Q and the total centre of mass energy available S is small.
These corrections are important for several processes within the kinematical range of the LHC, including heavy flavour production, Higgs production in gluon fusion and Drell-Yan. This talk will discuss recent developments on small-x resummation in differential cross sections in rapidity, transverse momentum and invariant mass and their application to heavy flavour production at the LHC and Parton Distribution Function determination. Additionally, an extension of the resummation of next-to-leading logarithms for inclusive cross sections will be presented, using a Higgs-induced Deep Inelastic Scattering as an explicit case study.

Low x, PDFs and hadronic final states / **49**

TMD gluon density at low x and soft and hard processes at LHC energies

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Transverse momentum dependent (TMD) parton distributions in a proton are important in high energy physics from both theoretical and phenomenological points of view. Using the latest LHC data on the inclusive soft hadron production at small transverse momenta, we determine the parameters of the initial TMD gluon density, derived within the soft QCD model at the low scale $\mu_0 \sim 1 - 2$~GeV.
Then, we apply the Catani-Ciafaloni-Fiorani-Marchesini (CCFM) evolution equation to extend the obtained TMD gluon density to the whole kinematical region. Using this TMD obtained at both low and large Q^2 data on hard processes of b-jet production, Higgs production and the structure functions F_{2c}, F_{2b} can be described

quite satisfactorily.

Low x, PDFs and hadronic final states / **79**

News from NNPDF

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I will present some recent developments in the understanding of theoretical and experimental uncertainties in PDFs, with special emphasis on the features of NNPDF 4.0, the regularisation of experimental covariance matrices and the propagation of matched scale uncertainties.

Low x, PDFs and hadronic final states / **38**

Small-x resummation in PDF fits and future prospects

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I will review recent results on the inclusion of small-x resummation in PDF fits, with emphasis on where we are and where we can/shall go in future, especially in the light of future higher energy colliders and improved theoretical accuracy.

Low x, PDFs and hadronic final states / **23**

Determination of proton parton distribution functions using ATLAS data

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We present fits to determine parton distribution functions (PDFs) using a diverse set of measurements from the ATLAS experiment at the LHC, including inclusive W and Z boson production, ttbar production, W+jets and Z+jets production, inclusive jet production and direct photon production. These ATLAS measurements are used in combination with deep-inelastic scattering data from HERA. Particular attention is paid to the correlation of systematic uncertainties within and between the various ATLAS data sets and to the impact of model, theoretical and parameterisation uncertainties.

Low x, PDFs and hadronic final states / **139**

New constraints on PDFs with CMS data

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Photon-photon physics and hard diffraction / **128**

Discussion session: photon photon and hard diffraction

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Photon-photon physics and hard diffraction / **57**

Photon-photon transition form factors of axial vector quarkonia in a light front approach

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We present a detailed study of transition form factors for axial-vector meson production via the two-photon fusion process $\gamma^*\gamma^* \to 1^{++}$, with space-like virtual photons in the initial state and a P-wave axial-vector quarkonium in the final state. In this analysis, we employ the formalism of light-front quarkonium wave functions obtained from a solution of the Schr\"odinger equation for a selection of interquark potentials for $Q\bar{Q}$ interaction.

Photon-photon physics and hard diffraction / **97**

Quarkonia Production in Ultra-peripheral PbPb collisions at LHCb

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Measurements of quarkonia production in peripheral and ultra-peripheral heavy-ion collisions are sensitive to photon-photon and photon-nucleus interactions, the partonic structure of nuclei, and the mechanisms of vector-meson production. LHCb has studied both coherent and incoherent production of ⍰/⍰ mesons in peripheral and ultra-peripheral collisions using PbPb data at forward rapidity with the highest precision currently accessible. Here we will present these measurements, along with comparisons with the latest theoretical models and with results from other experiments.

Photon-photon physics and hard diffraction / **110**

Recent ALICE results on ultra-peripheral heavy-ion collisions

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Photon-photon and photonuclear reactions are induced by the strong electromagnetic fields generated by ultrarelativistic heavy-ion collisions. These processes have been extensively studied in ultra-peripheral collisions with impact parameters larger than twice the nuclear radii. Photoproduced quarkonia can probe the nuclear gluon distributions at low Bjorken-x. The continuum dilepton production could be used to further map the electromagnetic fields produced in heavy-ion collisions and to study possible induced or final state effects in overlapping hadronic interactions.
The measurement of J/ψ photoproduction off hadrons sheds light onto the initial state of QCD targets and provides important constraints to the initial conditions used in hydrodynamical models of heavy ion collisions. We will present recent ALICE results using ultra-peripheral p-Pb and Pb-Pb collisions.

Photon-photon physics and hard diffraction / 88

Exclusive production of vector mesons at LHCb

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Studies of vector meson exclusive production in pp collisions will be discussed. At the LHC energy, measurements of diffractive events probe interesting QCD phenomenology, including the nature of pomerons, low-x gluon distributions and saturation effects.

Photon-photon physics and hard diffraction / 66

Light-by-light scattering - an ongoing challenge for theory (forward rapidity) and experiment (low invariant mass)

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Till recently, light-by-light scattering ($\gamma\gamma \to \gamma\gamma$) was not accessible for experiments because the corresponding cross section is relatively low. Measurements of diphotons in ultra-peripheral collisions (UPCs) of lead-lead nuclei have been reported recently by the ATLAS and CMS Collaborations. Our theoretical results 1 based on the equivalent photon approximation in the impact parameter space agree with the current data.
We will discuss extending studies to lower $\gamma\gamma$ energies where photoproduction of pseudoscalar and scalar resonances contributes to the final two-photon state. In addition, we consider the dominant background that arises from $\gamma\gamma$ fusion into pairs of neutral pions. Such π^0-pairs contribute to the background when only two of the four decay photons are within the experimental acceptance, and the other two photons escape undetected. We will discuss in detail how to reduce the unwanted background.
We will present differential distributions and total cross section in ultra-peripheral Pb-Pb collisions at $\sqrt{s_{NN}} = 5.05$ and 5.52 TeV and cross section for Ar-Ar collisions at the energy equal to 6.3 TeV 3. Results for ALICE, ATLAS, CMS and LHCb acceptance will be presented.

We will also try to elaborate on the possibility of measuring two photons in the forward/backward rapidity range with very small cut on the photon's transverse momentum, i.e. $p_{t,\gamma} > 1$ GeV. It will be shown that FoCal (ALICE) and other LHC forward detectors provide opportunity to study processes that are not identified in more central areas of rapidity. Predictions [4] indicate the importance of higher order mechanisms such as two-gluon exchange 2 or the VDM-Regge model.

References:
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Light-by-light scattering in ultraperipheral Pb-Pb collisions at energies available at the CERN Large Hadron Collider,
Phys. Rev. C93 (2016) 044907,
2. M. Klusek-Gawenda, W. Schaefer and A. Szczurek,
Two-gluon exchange contribution to elastic $\gamma\gamma \to \gamma\gamma$ scattering and production of two-photons in ultraperipheral ultrarelativistic heavy ion and proton-proton collisions,
Phys. Lett. B761 (2016) 399,
3. Z. Citron, M. Klusek-Gawenda, et al.,
Report from Working Group 5: Future physics opportunities for high-density QCD at the LHC with heavy-ion and proton beams,
CERN Yellow Rep. Monogr. 7 (2019) 1159-1410
4. M. Klusek-Gawenda, A. Szczurek, paper in preparation

Photon-photon physics and hard diffraction / 89

Hard diffraction and proton tagging at the LHC

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Many standard model processes in proton-proton collisions at the LHC are produced through diffractive interactions where one or both protons may survive the collisions. The dominant production of diffractive interactions is where only one proton emerges intact (hard single diffraction). We propose using the LHC data to study the diffractive production of EW boson and heavy flavor quarks as a new probe for constraining diffractive components.

Photon-photon physics and hard diffraction / 56

Anomalous coupling studies with intact protons at the LHC

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We describe the gain on sensitivities to quartic □□□□, □□□□ and □□□□ anomalous couplings and to the search for Axion-Like Particles by two or three orders of magnitude with respect to standard methods at the LHC by tagging intact protons in the final state, and matching the information from the intact protons and the □□, □□, □□, □□ in the main CMS and ATLAS detectors. We will also describe the sensitivity to □□□□⁻ that was recently accepted for publication.

Photon-photon physics and hard diffraction / 33

Photon-induced processes with tagged protons at CMS

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The Precision Proton Spectrometer (PPS) is a new subdetector of CMS introduced for the LHC Run 2. The talk will present the recent results on photon-induced processes explored with PPS, illustrating the unique sensitivity which can be achieved using proton tagging.

Photon-photon physics and hard diffraction / 106

Photon-photon fusion and tau g-2 measurement

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Relativistic heavy-ion beams at the LHC are accompanied by a large flux of equivalent photons, leading to multiple photon-induced processes. This talk presents a series of measurements of such processes performed by the ATLAS Collaboration. New measurements of exclusive dilepton production
(electron, muon, and tau pairs) are discussed. Furthermore, the tau-pair production measurements can constrain the tau lepton's anomalous magnetic dipole moment. High statistics
measurements of light-by-light scattering shown in this talk provide a precise and unique opportunity to investigate extensions of the Standard Model, such as the presence of axion-like particles. Presented measurements of muon pairs produced via two-photon scattering processes in hadronic Pb+Pb collisions provide a novel test of strong-field QED by exploiting correlations between the lepton pair and second-order event-plane, which can potentially be a sensitive electromagnetic probe of the quark-gluon plasma. Results are compared with recent theory calculations.

Photon-photon physics and hard diffraction / **32**

Photon-photon and photon-proton physics in ultraperipheral collisions at CMS

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Recent CMS results from gamma-gamma and gamma-p interactions in UPC will be reviewed.

Recent theoretical results on QCD and saturation / **70**

Effect of Sudakov factor in Golec-Biernat Wusthoff saturation model

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We investigate improvements on models of dipole cross-section, one of which was originally proposed by Golec-Biernat and W\"usthoff (GBW), and the other is a DGLAP improved model proposed by Bartels, Golec-Biernar and Kowalski (BGK), which has improved small dipole behaviour.
Both models have been very successful in describing saturation phenomenon in small x DIS.
In this study, we incorporate Sudakov factor which makes the dipole cross-section hard scale Q^2 (photon virtuality) dependent.
The parameters are fitted to HERA data and χ^2 value are obtained for each model.
The GBW model, which showed strong deviation from the data with Q^2 above $\sim 50\mathrm{GeV}^2$, improves noticeably at large Q^2 due to the hard scale dependence. For the data $Q^2 < 100\mathrm{GeV}^2$, the χ^2 value is reduced by $\sim 10\%$. The χ^2 value of the BGK model improves by $\sim 15\%$, for the data $Q^2 < 650\mathrm{GeV}^2$.

Recent theoretical results on QCD and saturation / **61**

A one-loop central-emission vertex for two gluons in N=4 SYM

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There has been much recent progress towards extending the BFKL equation to next-to-next-to-leading logarithmic (NNLL) accuracy. One of the remaining ingredients of the BFKL kernel is the one-loop central-emission vertex (CEV) for two gluons which are not strongly ordered in rapidity. In this talk I will discuss our recent extraction of this vertex in N=4 super Yang-Mills (SYM) theory, which is a component of the two-gluon CEV in QCD. We will see that the central next-to-multi Regge limit captures much of the colour and kinematic complexity of one-loop gluon amplitudes in general kinematics, while still leading to tractable expressions. I will emphasise the further simplifications that occur when considering the interference of the one-loop CEV with its tree-level counterpart.

Recent theoretical results on QCD and saturation / **68**

High-energy signals from heavy-flavor physics

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Heavy-flavored emissions have been always considered as an excellent channel to test properties of Quantum chromodynamics (QCD) at present and future colliders. Among different regimes, in which heavy-flavor production can be investigated, we focus our attention on the semi-hard one, where $s \gg Q^2 \gg \Lambda_{QCD}$ (s is the squared center-of-mass energy, $\{Q^2\}$ a (set of) hard scale(s) characteristic of the process and Λ_{QCD} the QCD mass scale). Here, we build predictions in a hybrid collinear/high-energy factorization, in which the standard collinear description is supplemented by the Balitsky-Fadin-Kuraev-Lipatov resummation of large energy logarithms. The definition and the study of observables sensitive to high-energy dynamics in the context of heavy-flavor physics has the double advantage of (i) allowing to get a stabilization of the BFKL series under higher order corrections and (ii) providing us with an auxiliary tool to investigate heavy-flavor production in wider kinematical ranges.
Moreover, the heavy flavor production represents a fertile ground to study the interplay between different kind of resummation.
Hence, we propose a scientific program on heavy flavor physics at high energy that starts from the production of open states, with the ultimate goal of considering bound states (such as heavy-light mesons and quarkonia).
In this talk, after a brief overview on the theoretical set-up of high-energy factorization in the case of heavy-quark production, we will present some recent phenomenological analyses involving heavy-quark open states as well as bound states.

Recent theoretical results on QCD and saturation / **77**

Recent developments in exclusive photoproduction of excited vector mesons

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I will briefly overview the current status of phenomenological research in exclusive and diffractive photoproduction of excited vector mesons. The talk would cover the formalism and the key results on photo- and electroproduction observables of both heavy quarkonia states and light vector mesons in the color dipole picture. The key challenges in QCD modelling of such reactions including the basic aspects of low-x QCD dynamics and saturation would be outlined.

Recent theoretical results on QCD and saturation / **45**

Production of forward charm and neutrinos and unintegrated gluon distributions at very small x

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We discuss production of forward charm/anticharm quarks,
D mesons and neutrinos/antineutrinos from their semileptonic decays
in proton-proton collisions at the LHC energies.
The calculation is preformed within k_t-factorization
and hybrid model using different unintegrated gluon distribution
functions (UGDFs) from the literature.
We include gluon-gluon fusion, intrinsic charm (IC) as well as
recombination mechanisms.
We compare our results to the LHCb data for different
rapidity bins in the interval $2 < y < 4.5$.
A good description is achieved for the Kimber-Martin-Ryskin UGDF.

We also show results for the Kutak-Sapeta UGDF,
both in the linear form and including nonlinear effects.
The nonlinear effects play a role only at very small transverse
momenta of D^0 or $\bar{D}^0$ mesons. The IC and recombination
models are negligible at the LHCb kinematics. Both the mechanisms
start to be crucial at larger rapidities and dominate over
the standard charm production mechanisms.
At high energies there are so far no experiments probing this region.
We present uncertainty bands for the both mechanisms.
Decreased uncertainty bands will
be available soon from fixed target experiments p + A.
The recombination component leads to production asymmetry for
quarks ($c \neq \bar{c}$)
and in consequence for mesons ($D^0 \neq \bar{D}^0$).
We present also energy distributions for forward neutrinos
to be measured by the forward physics facilities such as FASERν.
We show results for electron, muon and tau neutrinos.
Again different components are shown separately.
The presentation is based on a paper in preparation 1.

1 R. Maciula and A. Szczurek, a paper in preparation.

Recent theoretical results on QCD and saturation / **41**

On NLO BFKL impact factors from NLO collinear amplitudes

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We construct a framework that may be used to compute NLO kT-dependent impact factors from NLO on-shell parton scattering amplitudes. The key point of the method is an extension to the NLO accuracy of the auxillary parton method commonly used in the LO calculations. With the high energy (Regge) factorization at the NLO, the collinear scattering amplitudes are decomposed into the NLO impact factors and the Green's function coming from the QCD evolution. We describe in detail the treatment in the kT factorization of infrared singularities that appear in the NLO collinear amplitudes.

Recent theoretical results on QCD and saturation / **133**

Discussion session: AdS CFT, high energy resummation

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Recent theoretical results on QCD and saturation / **53**

Production of 1S, 2S, 1P quarkonium state production in light-cone $k_\perp$-factorization approach

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We review our calculations of η_c(1S,2S) prompt production in proton-proton collisions at $\sqrt{s} = 7\,, 8\,, 13\,\mathrm{TeV}$, as well as χ_{c0}(1P) and χ_{b0}(1P). The matrix element of the $g^*g^* \to \mathcal{Q}$ is found by taking into account the proper colour factors and coupling constant to quarkonia electromagnetic form factors for $\gamma^*\gamma^* \to \mathcal{Q}$. The space-like form factors for both off-shell photons are obtained using the light-cone potential approach for the wave functions of $c\bar{c}$ or $b\bar{b}$ bound states.

Theoretical uncertainties of our approach are found by performing the analysis with two different unintegrated gluon densities and with five distinct models of the $Q\bar{Q}$ interaction potentials consistent with the meson spectra. We have found rather different results for discussed potential models. In the case of the 1P state, we considered separately transversal as well longitudinal contribution to the differential cross section in transverse momentum of the meson.

Recent theoretical results on QCD and saturation / **52**

Mechanisms of fully heavy tetraquark production in proton-proton collisions

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We discuss the production mechanism of a new state,
a fully charm tetraquark, discovered two years ago by the LHCb at
M = 6.9 GeV in the $J/\psi J/\psi$ channel.
Both single parton scattering (SPS) and double parton scattering (DPS)
mechanisms are considered. We calculate the distribution in the invariant
mass of the four-quark system M_{4c} for SPS and DPS production of
$cc\bar{c}\bar{c}$ in the k_t-factorization approach with modern
unintegrated gluon distribution functions (UGDFs).
The so-calculated contribution of DPS is almost two orders of
magnitude larger than the SPS one, but the tetraquark formation
mechanism is unknown at present.
We construct a simple coalescence model of the tetraquark out of
$c\bar{c}c\bar{c}$ continuum.
Imposing a mass window around the resonance position we calculate the
corresponding distribution in $p_{t,4c}$ – the potential tetraquark
transverse momentum. The cross section for the $J/\psi J/\psi$ continuum
is calculated in addition, again including SPS (box diagrams) and
DPS contributions which are of similar size.
The formation probability is estimated trying to reproduce
the LHCb signal-to-background ratio. The calculation of the SPS
$gg \to T_{4c}(6900)$ fusion mechanism is performed in the
k_T-factorization approach assuming different spin scenarios
(0^+, 0^- and 2^+). The 2^+ and 0^+ assignment is preferred over
the 0^- one by a comparison of the transverse momentum distribution
of signal and background with the LHCb preliminary data assuming
the SPS mechanism dominance.
There is no microscopic approach for the DPS formation mechanism
of tetraquarks at present as this is a complicated multi-body problem.

We do similar analysis for FCC energy $\sqrt{s}$ = 100 TeV.
We predict the production cross section order of magnitude larger
than its counterpart for the LHC.
We discuss also a possibility to observe the T_{4c} state in the
$\gamma\gamma$ channel. The signal-to-background ratio is estimated.

We discuss also production of $c\bar{c}b\bar{b}$ tetraquarks and
discuss how the results depend on the mass of such an object.

The presentation will be partially based on our paper 1.

1 R. Maciula, W. Schaefer and A. Szczurek,
"On the mechanism of $T_{4c}(6900)$ tetraquark production",
Phys. Lett. B812 (2021) 136010.

Recent theoretical results on QCD and saturation / 30

J\psi production in high multiplicity pp and pA collisions

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In this talk I will present analysis of J/ψ yield and polarization in high multiplicity hadron collisions using the CGC+NRQCD framework. Some predictions for pp and pA collisions at LHC energies will be presented.

Recent theoretical results on QCD and saturation / 109

Quark and gluon Helicity evolution at small-x: Revised and updated.

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Recent theoretical results on QCD and saturation / 126

Discussion session: CGC, saturation

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Recent theoretical results on QCD and saturation / 12

Next-to-leading order photon+jet production

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Using the CGC effective theory together with the hybrid factorisation, we study forward photon+jet production in proton-nucleus collisions beyond leading order. We first compute the "real" next-to-leading order (NLO) corrections, i.e. the radiative corrections associated with a three-parton final state, out of which only two are being measured. Then we move to the "virtual" NLO corrections to dijet production, in which a gluon loop is included as a part of the amplitude, before or after the measurement. Each of these loop diagrams diverges, and we explain our treatment in order to obtain finite expression for the cross section.
We explicitly work out the interesting limits where the unmeasured gluon is either a soft, or the product of a collinear splitting. We find the expected results in both limits: the B-JIMWLK evolution

of the leading-order dijet cross-section in the first case (soft gluon) and, respectively, the DGLAP evolution of the initial and final states in the second case (collinear splitting).

Recent theoretical results on QCD and saturation / **44**

Sudakov suppression and gluon saturation at NLO

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We study inclusive dijet production in deep inelastic scattering at NLO within the Color Glass Condensate Effective Field Theory. We begin by studying this process in general small-x kinematics where we: (i) show that the differential cross-section is infrared and collinear safe, (ii) demonstrate the factorization of large energy/rapidity logarithms which can then be resummed via JIMWLK renormalization, and (iii) compute explicit expressions for the impact factor.

We then specialize in the transverse back-to-back kinematics where this process is sensitive to unpolarized and linearly polarized parts of the Weizsäcker-Williams (WW) gluon distribution. We extract from the impact factor the large Sudakov double and single logarithms at finite Nc. We show that small-x and Sudakov resummation can be performed simultaneously provided that the small-x evolution of the WW distribution, formulated in terms of the projectile rapidity, is amended by a kinematic constraint that imposes lifetime ordering of successive gluon emissions. We also comment on non-logarithmically enhanced terms in the impact factor that can break TMD factorization at NLO in the saturation regime.

Recent theoretical results on QCD and saturation / **95**

Evolution of initial stage fluctuations in the Glasma

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By describing the initial stage of heavy ion collisions in terms of freely-evolving classical fields, we perform a first-principles calculation of the energy density one- and two-point correlation functions at finite proper time. Our approach allows us to systematically resum the contributions of high momentum modes that would make a power series expansion in proper time divergent. In order to obtain numerical results we evaluate the field correlators using the Glasma Graph approximation and the simple GBW saturation model. Our results provide analytical insight into the pre-equilibrium phase of heavy ion collisions. Upon further refining of our calculations, our expressions could be applied to constrain the initial conditions of hydrodynamical evolution, as well as potentially save computing time for models based on numerical solutions to the Yang-Mills equations.

Recent theoretical results on QCD and saturation / **63**

NLO JIMWLK with massive quarks

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High energy evolution of scattering amplitudes is governed by the JIMWLK Hamiltonian. At NLO it involves quark contributions. The NLO JIMWLK Hamiltonian with massless quarks has been known for some time.

Yet, the quest for precision requires inclusion of effects due to quark masses. This gap has been filled.

Recent theoretical results on QCD and saturation / 111

Gluon dipole factorization and saturation in diffractive dijet production

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Using the color dipole picture for DIS, we study the production of a pair of jets initiated by a quark and an antiquark, through coherent diffraction. The transverse momenta of the two jets are taken to be larger than the target saturation momentum. Then the typical final-state configurations are such that the hard dijets are accompanied by a semi-hard gluon jet, with transverse momentum of the order of the saturation momentum so that it scatters strongly. For these 2+1 jet configurations, we show that the emission of the semi-hard gluon and its subsequent scattering with the target are factorised in terms of a gluon-gluon dipole. The hard factor describes the hard dijets, while the semi-hard one stands for the unintegrated gluon distribution of the Pomeron. When integrating out the dijet imbalance, we obtain collinear factorisation where the initial condition for the DGLAP evolution is set by gluon saturation. Integrating the kinematics of all 3 jets, we obtain the quarkantiquark-gluon contribution to the diffractive structure function in collinearly-factorised form.

Recent theoretical results on QCD and saturation / 31

Exclusive vector meson production at next-to-leading order in the Color Glass Condensate framework

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Exclusive vector meson production is a powerful process to probe the small Bjorken-x structure of protons and nuclei, as such processes are especially sensitive to gluonic structure and also provide access to the spatial distribution of small-x gluons in nuclei. A powerful theoretical framework to study such high-energy processes is the Color Glass Condensate (CGC) effective field theory. So far, most calculations in the CGC framework have been done at the leading order. Recent theoretical developments on the NLO heavy vector meson wave function 1 and the NLO virtual photon light-front wave function [2,3] have made it possible to go beyond the leading order in exclusive vector meson production, allowing us to calculate this process at NLO in the dipole picture for the first time. In this talk, I will discuss the calculation of the NLO corrections to heavy vector meson production in the nonrelativistic limit [4,5], and to light vector meson production in the limit of large photon virtuality [6].

1 M. Escobedo and T. Lappi, Phys.Rev.D 101 (2020) 3, 034030, arXiv:1911.01136 hep-ph G. Beuf, T. Lappi and R. Paatelainen, Phys. Rev.D 104 (2021) 5, 056032, arXiv:2103.14549 hep-ph G. Beuf, T. Lappi and R. Paatelainen, arxiv:2204.02486 [hep-ph]
[4] H. Mäntysaari and J. Penttala, Phys. Lett.B 823 (2021), 136723, arXiv:2104.02349 [hep-ph]
[5] H. Mäntysaari and J. Penttala, arXiv:2204.14031
[6] H. Mäntysaari and J. Penttala, Phys.Rev.D 105 (2022) 11, 114038, arXiv:2203.16911 [hep-ph]

Recent theoretical results on QCD and saturation / **73**

Diffractive structure function in the dipole approach

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We calculate 1 the contribution from the $q\bar{q}g$ state to the small-x diffractive cross section in deep inelastic scattering in the saturation regime. The obtained cross section is finite by itself and a part of the full next-to-leading order result for the diffractive structure function. We perform the calculation in exact kinematics in the eikonal limit, and show that the previously known high Q^2 and large M_X^2 results for the structure functions can be extracted from our results in the appropriate limits. We furthermore discuss the steps required to obtain the full next-to-leading order results for the structure functions.

1 G. Beuf, H. Hänninen, T. Lappi, Y. Mulian and H. Mäntysaari,
"Diffractive deep inelastic scattering at NLO in the dipole picture: the $q\bar{q}g$ contribution," [arXiv:2206.13161 [hep-ph]].

Recent theoretical results on QCD and saturation / **20**

Signature of Accidental Symmetry Breaking in Two Particle Correlations Within the CGC

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In this work, we calculate the double-inclusive gluon production within the framework of the dense-dilute Color Glass Condensate (CGC) approach.
As a novelty, we provide the contribution accounting for the quantum correction in which the two gluons come from a single projectile source, thus giving renewed insights about a breaking of the accidental symmetry of the CGC which straightforwardly reveals the presence of odd harmonics at leading order in the eikonal expansion.

Recent theoretical results on QCD and saturation / **13**

NLO computation of diffractive di-hadron production in a saturation framework

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The cross-sections of diffractive double hadron photo- or electroproduction with large pT, on a nucleon or a nucleus, are calculated to NLO accuracy.
A hybrid formalism mixing collinear factorization and high energy kt factorization, more precisely the shockwave formalism, is used to derive the results.
The cancellation of divergences is explicitly shown, and the finite parts of the NLO differential cross-section are found. We work in arbitrary kinematics such that both photoproduction and leptoproduction are considered, making the results usable in order to detect saturation at both the future EIC or already at LHC, using UPC.

Recent theoretical results on QCD and saturation / **98**

The QCD shockwave approach at NLO: towards precision physics in gluonic saturation

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We review the recent developments of the QCD shockwave approach at Next-to-Leading Order. The general method of this effective action will be sketched, and several examples, in the case of diffractive processes, will be presented.

Soft and low-mass diffraction / **54**

The High-Energy Limit of $2 \to 2$ QCD scattering amplitudes

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The high-energy limit of $2 \to 2$ QCD scattering amplitudes has a rich history and recently there has been much renewed interest in the perturbative regime. In this talk, I review the salient features of this limit and present an overview of recent results. At Leading Logarithmic (LL) accuracy the partonic amplitude is governed by Regge poles in the complex angular momentum plane. Beyond LL, Regge cuts in this plane start to play an important role. First, I briefly review the Next-to-Leading Logarithmic (NLL) computations of the cuts, using BFKL evolution, which recently led to an all-order resummation of the infrared divergences of the amplitude and the determination of finite part to arbitrary orders. I then present very recent computations of the real part of the amplitude at Next-to-Next-to-Leading Logarithmic (NNLL) accuracy, using non-linear Balitsky-JIMWLK evolution, through four loops. At this logarithmic accuracy, for the first time both the Regge pole and the Regge cut contribute to the real part of the amplitude and I show how these can be systematically disentangled order-by-order in perturbation theory. Finally, I present new results for the three-loop Regge trajectory and impact factors, obtained upon comparing the Regge-limit analysis with state-of-the-art fixed-order computations in general kinematics.

Soft and low-mass diffraction / **25**

Measurement of multijet events and photon production with ATLAS

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The production of jets at hadron provides stringent tests of perturbative QCD. We present the latest measurements using proton-proton collision data collected by the ATLAS experiment at $\sqrt{s} = 13$ TeV. We will discuss the measurement of new event-shape jet observables defined in terms of reference geometries with cylindrical and circular symmetries using the energy movers distance. The results are unfolded for detector effects and compared to the state-of-the-art next-to-leading order parton shower generators. If ready, the measurement of strong coupling constant will be presented using the ratio of 3-jet to 2-jet events. Finally, prompt inclusive photon production is measured for two distinct photon isolation cones, R=0.2 and 0.4, as well as for their ratio.

Soft and low-mass diffraction / **135**

Discussion sssion: Odderon

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Soft and low-mass diffraction / 65

Odderon observation from elastic pp and ppbar difference and pp forward scattering: an update with answers to questions and objections

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The pp elastic cross section at 1.96 TeV, obtained from a data-driven extrapolation of the cross sections measured by TOTEM at 2.76, 7, 8, and 13 TeV, have been compared with the D0 ppbar elastic cross section at 1.96 TeV in the region of the diffractive minimum and the second maximum of the pp cross section 1. The two 1.96 TeV data sets have been found disagree at the 3.4σ level and thus provides evidence for Odderon exchange. These results have been combined with a TOTEM analysis of Odderon exchange based on the total cross section and the ρ parameter in pp elastic scattering 2. The combined significance is larger than 5σ and interpreted as the first observation of Odderon exchange.

In this presentation, a comprehensive list of questions and objections raised to the published analysis are answered and supplementary material is provided 3. These demonstrate that the methods and assumptions made for the extrapolation of the pp elastic cross section to 1.96 TeV and its comparison to the D0 measurement in ppbar are valid and reasonable, even conservative on key points, leading in fact to an conservative estimate for the significance. Same is true for the methods and choices made by TOTEM for the total cross section and the ρ measurements.

1 V.M. Abazov et al. (D0 and TOTEM Collaborations), Odderon Exchange from Elastic Scattering Differences between pp and ppbar Data at 1.96 TeV and from pp Forward Scattering Measurements, Phys. Rev. Lett. 127, 062003 (2021).
2 G. Antchev et al. (TOTEM Collaboration), First determination of the ρ parameter at √s = 13 TeV: probing the existence of a colourless C-odd three-gluon compound state, Eur. Phys. J. C. 79, 785 (2019).
3 K. Österberg on behalf of D0 and TOTEM Collaborations, Odderon observation: explanations and answers to questions/objections regarding the PRL publication, in Proc. of Low-x Workshop 2021, arXiv:2202.03724 (2022).

Soft and low-mass diffraction / 22

Isolating the Odderon in central production in high energy pA and AA collisions

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We study the rapidity dependence of the central exclusive production cross sections of C-even mesons in pA and AA collisions, where A is a heavy ion. We observe qualitatively different behaviour of the contributions arising from photon-Odderon and Pomeron–Pomeron fusion mechanisms. This can be used to extract the Odderon signal from C-even mesons exclusively produced in the forward region. Estimates for f2 meson production, obtained using expected values of the Odderon cross section, indicate that the photon-Odderon contribution may exceed by a few times the Pomeron-induced background in Pb–Pb collisions. Moreover, the Odderon effect can be clearly seen in terms of the asymmetry in pA and AA collisions with the beam and target reversed. The photon–Odderon contribution has a large normalisation uncertainty but the enhanced cross-section in the

forward region combined with a large asymmetry increases the chance of experimentally detecting the Odderon.

Soft and low-mass diffraction / 74

Model-independent results for Odderon-exchange based on new TOTEM data at 8 TeV

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We analyze, model-independently, the scaling properties of the differential cross-section of elastic proton-proton cross-sections, including new TOTEM data published in 2022 at sqrt(s) = 8 TeV. We show that outside the signal region for Odderon exchange, the scaling function of elastic proton-proton data at 8, 7, 2.76 TeV and that of elastic proton-antiproton scattering data at 1.96 TeV are the same.
We confirm that the new TOTEM data at 8 TeV are vital as they strengthen further the statistically significant, model-independent signals for Odderon exchange. Last but not least, we present a new, simple, and straightforward method to demonstrate the existence of Odderon exchange from sqrt(s) = 0.546, 0.630, and 1.96 TeV proton-antiproton as well as sqrt(s) = 2.76, 7, 8 and 13 TeV proton-proton elastic scattering data, without any model-dependent contributions to the analysis of the statistical significance of odderon exchange.

Soft and low-mass diffraction / 50

The ReBB model at 8 TeV: Odderon exchange is a certainty

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The Real Extended Bialas-Bzdak (ReBB) model is shown here to describe, in the $0.37 \leq -t \leq 1.2$ GeV^2 region, the proton-proton elastic differential cross section data published by the TOTEM Collaboration at LHC at $\sqrt{s} = 8$ TeV center of mass energy. In this kinematic range, corresponding to the diffractive minimum-maximum region, a model-dependent Odderon signal higher than 18 σ is obtained by comparing the ReBB model prediction for the $p\bar{p}$ elastic differential cross section to this TOTEM measured pp elastic differential cross section data at 8 TeV. However, when combining this signal with the Odderon signals from the ReBB model in the $0.37 \leq -t \leq 1.2$ GeV^2 four-momentum-transfer range at $\sqrt{s} = 1.96$, 2.76 and 7 TeV, it turns out that the combined significance is dominated not by the new 8 TeV but by that of earlier 7 TeV TOTEM data, that carry an even larger Odderon effect. Thus, in any practical terms, within the framework of the ReBB model, the Odderon signal in the limited $0.37 \leq -t \leq 1.2$ GeV^2 and $1.96 \leq \sqrt{s} \leq 8$ TeV kinematic region is not a probability, but a certainty. We show also that the $H(x)$ version of the ReBB model works reasonably well at 8 TeV in the $0.37 \leq -t \leq 0.97$ GeV^2 region.

Soft and low-mass diffraction / 3

Universal scaling properties of proton-proton elastic scattering

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he differential cross section of proton-proton elastic scattering ⊠⊠/⊠⊠, as a function of the magnitude

of the four-momentum transfer squared |□|, evolves in a consistent way with □√ at LHC energies, all the curves being translated in the (|□|, □□/□□) plane for different center-of-mass energies. This means that the cross sections vary according to a scaling law in center-of-mass energy □√ and on |□|.
These features suggest there are hidden universal properties of elastic scattering. Based on these empirical observations, and taking inspiration from saturation models, we propose a simple scaling law for proton-proton elastic scattering. The differential cross sections measured by TOTEM at □√=2.76,7,8, and 13 TeV fall in a universal curve when they are mapped to the scaling variables □□/□|□|(□/TeV2)−0.305 versus (□/TeV2)0.065(|□|/GeV2)0.72. In addition, we explore the implications of this scaling law in the impact parameter picture of the scattering amplitudes.

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Discussion session: soft and low mass diffraction

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Soft and low-mass diffraction / 11

Evolution equation for elastic scattering of hadrons

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We turn high energy elastic scattering of hadrons into an initial value problem using an evolution equation based on the Regge Field Theory, which has a form of the complex nonlinear reaction-diffusion equation, with time being played by the logarithm of energy. The initial conditions are provided by the data-driven models for the real and imaginary parts of the amplitude. Numerical calculations of pp differential cross sections and forward quantities for LHC energies agree very well with experimental data extending up to, and including the diffractive cone. Furthermore, we show that at current accessible energies the non-linear effects play an important role, as the impact parameter space profiles approach the unitarity bound. The equation also predicts some other effects discussed in the literature, like the hollowness of nuclear matter or existence of stationary points in momentum transfer t.

Soft and low-mass diffraction / 29

Hunting for QCD Instantons at the LHC in the forward proton mode

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We discuss the current status of the ongoing project on
searches for the QCD instantons at hadron colliders
in events with large rapidity gaps. These gaps in rapidity
are formed by either Pomeron or photon exchanges or a combination
of the two. We computed for the first time the relevant
differential cross-sections for a complete set of instanton production
in single diffraction and CEP
processes at the LHC, including gluon-induced and quark-induced
amplitudes, and also show that the largest contribution to CEP comes

from processes with Pomeron exchanges where a single gluon from each
Pomeron couples to the instanton.
A strategy of how to search for QCD instantons of invariant
mass 20 - 60 GeV in diffractive events at the
LHC is outlined. By imposing appropriate cuts on final states in SD, it is expected that we can select the kinematical region where the Instanton
signal exceeds the SM background by at least 2.5.
The rate is expected
to be large enough to measure Instanton production at the LHC
in the events with a single tag at low Luminosity.
The work is still very much in progress.

Soft and low-mass diffraction / **19**

Nuclear effects in coherent photoproduction of heavy quarkonia

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Coherent photoproduction of heavy quarkonia on nuclear targets is studied within the QCD color dipole formalism including several main phenomena:
-i) The higher-twist nuclear shadowing related to the $Q\bar{Q}$ Fock state of the photon;
-ii) The correlation between impact parameter of a collision $\vec{b}$ and dipole orientation $\vec{r}$;
-iii) The leading-twist gluon shadowing corresponding to higher Fock components of the photon containing gluons;
-iv) Reduced effects of quantum coherence in a popular Balitsky-Kovchegov equation compared to calculations, which are frequently presented in the literature.
Our calculations of differential cross sections are in good agreement with recent ALICE data on charmonium production in ultra-peripheral nuclear collisions. We present also predictions for coherent photoproduction of other quarkonium states ($\Psi'(2S)$, $\Upsilon(1S)$ and $\Upsilon'(2S)$) that can be verified by future measurements at the LHC.

Soft and low-mass diffraction / **64**

GRANIITTI: Towards a deep learning enhanced MC event generator for high energy diffraction

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I will introduce the physics scope and state-of-the-art technology of GRANIITTI [github.com/mieskolainen/graniitti], a fully multithreaded C++17 language-driven Monte Carlo event generator designed especially for the central exclusive glueball searches and studies at the LHC and beyond. The extendable set of processes span currently from $\gamma\gamma$-EW and Durham QCD to non-perturbative 'minimal Pomeron' and 'tensor Pomeron' based.

For the low-mass central (semi)-exclusive *pp*-diffraction, GRANIITTI is currently the only fully open source generator providing multi-resonance & continuum scattering amplitudes with parametric spin correlations, simultaneously with differential screening (absorption) loop effects and forward proton excitation. I will compare the simulations against quite recent fiducial cross-section measurements of the process $pp \to p + X + p$ from the STAR experiment at $\sqrt{s} = 0.2$ TeV. These measurements include numerous differential distributions, for a pion-, kaon- and proton-pair central final states X together with measured forward protons. The crucial soft model parameter estimation or 'tuning' challenge is automated with HEPData input via cutting-edge gradient-free global optimiza-

tion algorithms – used in deep learning for a model hyperparameter optimization – and integrated here as a new HPC-distributable part of the generator.

Finally, I will outline ambitious future directions towards GRANIITTI v2. These include utilizing deep learning for more flexible data-driven Lorentz covariant soft scattering amplitudes or individual building blocks, such as 'deep Pomeron' and more efficient MC importance sampling based on invertible high-dimensional density function networks.

Soft and low-mass diffraction / 99

Multiple pion pair production in a Regge based model

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Central diffractive event topologies at the LHC energies can be identified by two different approaches. First, the forward scattered protons can be measured in Roman pots. Second, a veto on hadronic activity away from midrapidity can be imposed to define a double gap topology. Such a double gap trigger has been implemented by the ALICE collaboration in Run 1 and Run 2 of the LHC. The analysis of these events allows to determine the charged particle multiplicity within the acceptance. The excellent particle identification capabilities of ALICE allows to study two track events both in the pion and kaon sector. Events with measured charged particle multiplicity larger than two can arise from multiple pair production.

I will outline a Regge based approach for modeling such multiple pair production.

Soft and low-mass diffraction / 100

Modeling photon radiation in soft hadronic collisions

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Soft hadronic collisions with multiple production of (anti)quarks accompanied with soft photon radiation are described in terms of higher Fock states of the colliding hadrons, which contain a photon component as well. The Fock state distribution functions are shaped with the Quark-Gluon String Model. Photon radiation by quarks is described within the color-dipole phenomenology. The results of calculations are in a good accord with available data in a wide range of of transverse momenta of the photons.

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The Low theorem for diffractive bremsstrahlung and the soft photon puzzle

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The anomalous excess of small-kT photons radiated along with multi-hadron production, is challenging the physics community over four decades, but no solution has been proposed so far. We argue that the problem is rooted in the comparison with an incorrect model, usually called "bremsstrahlung model".

The Low theorem, proven only for diffractive photon radiation, relates it to the elastic scattering amplitude. The latter is linked by the unitarity relation to the square of the multi-hadron production amplitude. Therefore the cross section of photon radiation from the final state of multi-hadron production is related to the inner radiation for the elastic hadronic amplitude, which was proven by Francis Low to vanish in the soft photon limit.

We propose an alternative color-dipole description for soft photon radiation, which well agrees with available data.

Soft and low-mass diffraction / 8

Precision small scattering angle measurements of proton-proton and proton-nucleus analyzing powers at the RHIC hydrogen jet polarimeter

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The Polarized Atomic Hydrogen Gas Jet Target polarimeter (HJET) is used to precisely, $\sigma_P^{\rm syst}/P \sim 0.5\%$, measure the absolute (vertical) polarization of the proton beams at the Relativistic Heavy Ion Collider (RHIC). At HJET, the recoil protons from the beam Coulomb-nuclear interference scattering ($0.0013 < -t < 0.018\,\mathrm{GeV}^2$) off the jet target are detected in the vertically oriented Si strips. Measuring time of flight, kinetic energy, and z-coordinate (discriminated by the Si strips) for each detected proton allows us to reliably isolate elastic pp scattering events. Since both beam a_b and target (the jet) a_j spin correlated asymmetries are measured concurrently (i.e., using the same events), the beam polarization can be related $P_{\rm beam} = P_{\rm jet} \times a_b/a_j$ to the jet one, $P_{\rm jet} \sim 0.96 \pm 0.001$, monitored by the Breit-Rabi polarimeter.

Low and well controllable background in the measurements allowed us to precisely determine, for 100 and 255 GeV proton beams, the single $A_{\rm N}(t) \sim 0.04$ and double $A_{\rm NN}(t) \sim 0.002$ spin analyzing powers with the experimental uncertainties of about $|\delta A_{\rm N,NN}(t)| \sim 2 \times 10^{-4}$. The hadronic spin-flip amplitude parameters r_5 and r_2 were reliably isolated. The Regge fit of the spin-flip amplitudes indicated that Pomeron single and double spin-flip couplings were well determined and found to be significantly different from zero.

For the proton-proton scattering at HJET, the inelastic events, $p + p_{\rm jet} \to \pi + X + p_{\rm jet}$ can be isolated at the momentum transfer range of about $0.004 < -t < 0.009\,\mathrm{GeV}^2$ and at the missing mass $M_{\pi X} > m_p + m_\pi$ range limited by the detector acceptance (and, thus, depending on the beam energy). It was found that the inelastic jet spin analyzing power $A_{\rm N}^j$ is significantly smaller compared to the elastic $A_{\rm N}$ while the beam spin $A_{\rm N}^b$ is significantly larger. The measured inelastic $A_{\rm N}^{b,j}$ grows if the missing mass $M_{\pi X}$ is decreased. For the beam spin asymmetry, large values of up to $A_{\rm N}^b(t, M_{\pi X}) \sim 35\%$ were found in the data analysis.

It was found that the HJET recoil spectrometer performance in the RHIC heavy ion beams is about the same as in the proton ones. This allowed us to measure $p^\uparrow A$ analyzing power at 100 GeV for the following ions $^2\mathrm{H}^+$ (d), $^{16}O^{8+}$, $^{27}\mathrm{Al}^{12+}$, $^{96}\mathrm{Zr}^{40+}$, $^{96}\mathrm{Ru}^{44+}$, $^{197}\mathrm{Au}^{79+}$. Also, the beam energy scan was done for d (9.9, 19.6, 31.3, and 100\,GeV) and Au (3.85, 4.59, 5.76, 9.8, 13.2, 19.5, 27.2, 31.2, and 100 GeV). No evidence of the quasi-elastic (breakup) events, the fraction $< 1\%$, was found in the Au elastic data. For the deuteron beam, the breakup fraction was evaluated to be about 5\% (for $t \sim -0.007\,\mathrm{GeV}^2$).

The considered possibility to precisely measure, using HJET, ^{3}He beam polarization at the Electron-Ion Collider will also be discussed.

Spin physics / 26

Forward proton measurements with ATLAS

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The elastic scattering of protons at 13 TeV is measured in the range of protons transverse momenta allowing the access to the Coulomb-Nuclear-Interference region. The data were collected thanks to dedicated special LHC beta* = 2.5km optics. The total cross section as well as rho-parameter, the ratio of the real to imaginary part of the forward elastic scattering amplitude, are measured and compared to various models and to results from other experiments. Measurements of exclusive di-pion production will also be discussed.

Spin physics / **34**

New constraints on PDFs with CMS data

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New constraints on PDFs using recent CMS data will be shown in this talk

Spin physics / **114**

Current Status and Future Prospects on Transverse-Momentum Distribution Functions

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Probing the structure and dynamics of matter has witnessed a dramatic development overthe last decades with new theoretical advances to probe nucleons and nuclei beyond just a one-dimensional approach through Transverse-Momentum Distribution (TMD) functions. TMDsprovide crucial insight into the confined motion of quarks and gluons with a transverse momen-tumkTinside a nucleon and nucleus.After a brief theoretical overview of various processes in both fixed-target and collider ex-periments probing TMDs, various experimental results will be reviewed, including results ob-tained by the COMPASS collaboration, at JLab, and the RHIC Spin program. An overview ofprospects at the future Electron-Ion Collider (EIC) facility accessing quark and gluon TMDswill be provided at the end.

Spin physics / **124**

Experimental Review on TMDs

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Spin physics / **125**

Discussion session: spin, GPD, TMD...

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Spin physics / 107

Accessing GPDs through the exclusive photoproduction of a photon-meson pair with a large invariant mass

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We study the exclusive photoproduction of a photon-meson pair with a large invariant mass, working at leading twist and leading order in the framework of QCD collinear factorisation. Explicitly, the produced meson is either a rho meson or a charged pion. This process allows us to extract generalised parton distributions. In particular, unlike in deeply-virtual Compton scattering and deeply-virtual meson production, considering a transversely-polarised rho meson in the final state enables us to access chiral-odd GPDs at the leading twist, which are not known experimentally.
We discuss the prospects of measuring this process at various experiments, such as JLab, EIC and LHC (in ultraperipheral collisions).

Spin physics / 42

Phenomenology of GPDs: status and perspectives

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Exclusive processes and their description in terms of Generalized Parton Distributions give us unique insight into the structure of hadrons. They have also become a key element of the experimental programs, especially at JLab and the forthcoming Electron-Ion Collider. I will review the main properties of GPDs, describe the status of the phenomenological studies, and the perspectives for their extraction from the data.

Spin physics / 71

Determination of Generalized Parton Distributions in the nucleon through exclusive electoproduction.

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I will present a review of measurements undertaken at various experiments
for determining the Generalized Parton Distributions in the nucleon. Results on Deeply Virtual Compton Scattering with exclusive single-photon
production as well as hard exclusive meson production have been obtained
at HERMES, JLab and COMPASS using electron or muon beams and nucleon
targets in various kinematic ranges. The measurements are sensitive to the
transverse extension of partons in the proton. Efforts are undertaken to
use them in global analyses to constrain the nucleon GPDs.

Spin physics / 37

On the odderon mechanism for transverse single spin asymmetry in the Wilczek-Wandzura approximation

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The recent PHENIX 1 and STAR 2 data on the nuclear dependence of the transverse single spin asymmetry calls for a careful investigation into potential theoretical mechanisms that would explain this data in a quantitative way. To that end we investigate the transverse single spin asymmetry in forward $p^\uparrow p$ and $p^\uparrow A$ collisions from the odderon mechanism suggested by Kovchegov and Sievert in 3. We first identify the relevant collinear parton distribution function (PDF) of the transversely polarized proton $p^\uparrow$ as the intrinsic twist-3 $g_T(x)$ distribution by confirming fully the results in 3 where they are obtained on a partonic level. We further argue that the complete polarized cross section in the collinear twist-3 framework must in general contain also contributions from the kinematical and the dynamical twist-3 PDFs, in addition to the the intrinsic twist-3 PDF. By restricting to the Wandzura-Wilczek (WW) approximation, where the dynamical twist-3 PDFs are dropped, we find, quite surprisingly, that the polarized cross section for inclusive hadron production is exactly zero at the next-to-leading order in the strong coupling [4]. Finally, we outline several opportunities for the odderon mechanism that either rely on going beyond the WW approximation or to the next-to-next-to leading order in α_s.

1 PHENIX, Phys. Rev. Lett. 123 (2019) 122001
2 STAR, Phys. Rev. D 103 (2021) 7, 072005
3 Kovchegov, Sievert, Phys. Rev. D 86 (2012) 034028
[4] SB, Kaushik, Vivoda, in preparation

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Unpolarized cross section and transverse single spin asymmetry of Z^0 in 500/510 GeV p+p collisions

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We present the preliminary results of unpolarized cross section and transverse single spin asymmetry (TSSA) of Z^0 measured by the STAR experiment. The cross section results combine 500/510 GeV p+p data from 2011, 2012, 2013 and 2017, corresponding to a total luminosity of 700 pb^{-1}. The differential Z^0 cross section, measured as a function of the boson's transverse momentum, provides important constraints on the energy dependence of the transverse momentum dependent parton distribution functions (TMDs). The TSSA of Z^0 is measured using 510 GeV $p^\uparrow$+p data from 2017 with the integrated luminosity of 350 pb^{-1}. This observable is sensitive to one of the TMDs, the Sivers function, which is predicted to have the opposite sign in $p + p \to W/Z + X$ from that observed in semi-inclusive deep inelastic scatterings. Our data aim to investigate the non-universality of the Sivers function.

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TMD phenomenology and Single Spin Asymmetries

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I will talk about phenomenology of Transverse Momentum Dependent distributions and the spin asymmetries observed in a variety of scattering processes.I will argue that those asymmetries have a common origin, namely they arise due to the quantum mechanical interference from multi-parton

states of the hadron's wave function. I will explain how the theoretical and phenomenological understanding of those correlations is related to the studies the 3-dimensional structure of hadrons at existing and future facilities, including the Electron-Ion Collider.

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Introductorion to the spin session

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Introduction to the spin session

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End of workshop

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Workshop conclusion

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Welcome

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