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Some recent results related to low-x and forward physics

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This is the write-up of the plenary talk on low-x and forward physics presented at the DIS2019 workshop. Recent results on photon-induced processes from HERA, RHIC and the LHC are discussed. The material covers advances relevant to the structure of nuclear targets, the potential of photon-induced processes to probe the quark-gluon plasma, results related to the proton structure and a discussion of dissociative production of vector mesons as a new window to study saturation at future electron-ion colliders.

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1. Introduction

This is a personal selection of topics based on the following constraints: that the results have not been presented in a recent plenary talk of the DIS meetings, that they are of potential interest to the DIS community and that I know the subject well enough, so that I can present and discuss it correctly. My apologies to the many nice results that are available and that I cannot cover due to lack of time during the presentation nor space in these proceedings.

All the topics discussed below can be classified as photon-induced reactions. The experimental results are from the HERA, RHIC and LHC facilities. At HERA, where electron (or positrons) were collided with protons, the photons are emitted by the electron (or positron). At RHIC and LHC the topics discussed involve heavy nuclei at relativistic speeds as sources of the quasi-real photons. In a semi-classical approximation the photon flux from these ions is proportional to the square of the electric charge of the particle, while the maximum energy is given by the boost of the incoming particles in the laboratory frame [1]. These characteristics make of heavy ions a high-intensity source of quasi-real photons converting RHIC and the LHC in high-energy photon–photon and photon–hadron colliders. A recent review of these topics can be found in [2].

In perturbative quantum chromodynamics (pQCD), the structure of hadrons changes both with the energy of the probe use to observe it as well as with the resolution of the probe. This last one provides the hard scale that allows for the application of pQCD. It is expected, that for a fixed scale, the number of partons—quarks and gluons—in a hadron will grow up to a point where there would be so many of them that they would recombined until a dynamic equilibrium, called saturation, is reached. This was predicted in the seminal paper [3] and recently reviewed in [4].

Even though several measurements have been shown to be consistent with saturation, up to now there is no universally accepted experimental demonstration of this phenomenon. The determination of where exactly, in the phase space of energy and scale, saturation sets in is one of the most interesting questions nowadays in pQCD. Part of this interest has been aroused by the measurements described below as well as by the proposal of new electron-ion colliders (EIC) [5, 6].

2. The structure of nuclei at low x

It is an experimental fact that the structure of a free nucleon is different than that of a nucleon embedded in a nucleus. This is known as shadowing; see e.g. [7]. One of the phenomena that is expected to contribute to shadowing is saturation. Furthermore, saturation is expected to set at smaller energies (corresponding to larger values of the so-called x-Bjorken) in nuclei that in nucleons [8]. Currently, there are two experimental facilities to study the energy evolution of the pQCD structure of nuclei, RHIC and LHC, while in the—hopefully near—future we expect to have an EIC.

One of the cleanest experimental tools to study the structure of hadrons at high energies is the exclusive production of a vector meson. This process, depicted in Fig. 1, is related in leading order pQCD in the collinear approach to the square of the gluon distribution of the target [10].

The STAR collaboration has presented [11] preliminary, and not fully corrected, results on coherent photoproduction of J/ψ at mid-rapidity in Au–Au ultra-peripheral collisions (UPC) at a centre-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 200$ GeV. Specifically, they presented the depen-

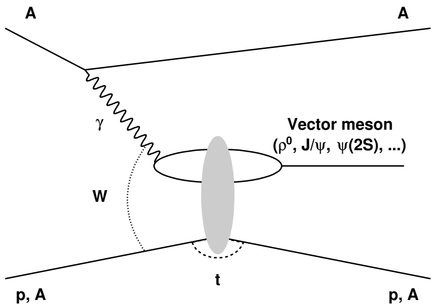

Figure 1: Sketch of exclusive photoproduction of a vector meson. The particle A (a proton or an ion at RHIC and LHC, and electron or positron at HERA and EIC) emits a photon which interacts at a centre-of-mass enegy W with the proton or ion coming in the opposite direction. As a result a vector meson is created and there is a momentum transfer $\sqrt{|t|}$ at the target vertex.

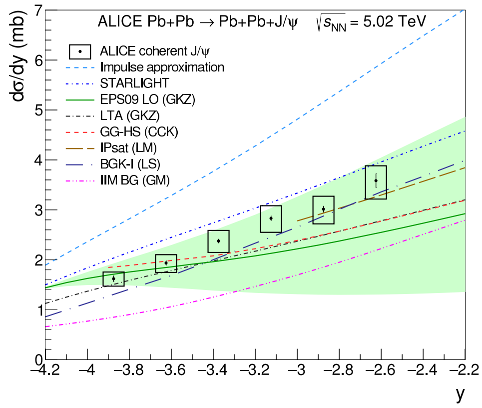

Figure 2: Rapidity dependence of the cross section for the coherent production of J/ψ vector mesons in ultra-peripheral Pb–Pb collisions by ALICE. Figure taken from [9].

dence on $|t|$, the square of the four momentum transferred at the target vertex. The distribution falls steeply, but not as fast as expected by the theoretical models they compared to. The discrepancy could be attributed to the missing corrections still to be applied to data. The models to which data are compared are the following three: (1) STARlight [12], based on a parameterisation of HERA data, the vector-dominance model, and a Glauber model without the inclusion of the elastic part;(2) a prediction based on the colour-dipole approach and including a subnucleon structure of nucleons in the transverse plane, so-called hot spots [13]; (3) a similar computation, but with the number of hot spots being energy dependent [14, 15].

The same process has been measured at the LHC in Pb–Pb UPC at $\sqrt{s_{\rm NN}} = 5.02$ TeV, but in this case at forward rapidity. Preliminary results have been reported by LHCb [16], while ALICE recently published their measurement [9]. The rapidity dependence of the cross section for the coherent production of J/ψ vector mesons is shown in Fig. 2, where the data are compared to theoretical models. Some observations are the following: the uncertainty of data is quite small, which places strong constraints on predictions; the impulse approximation which disregards nuclear effects is definitely not compatible with data; no model seems to describe data over all rapidities, although the model from [17] follows the trend reasonably close; a model which includes moderate shadowing [18] describes large rapidities while underestimates the measurement at smaller rapidities; a similar observation is valid for the energy-dependent hot-spot model mentioned above [15].

In Pb–Pb collisions at large rapidities there are two different contribution to the cross section, because either of the incoming ions can be the sources of the colliding photon (γ). One contribution has a large γPb centre-of-mass energy and the other has a small energy. To study the energy dependence of the γPb cross section, these two processes have to be separated. This requires to measure the Pb–Pb cross section at a given detector rapidity in at least two different impact parameter ranges.

One option is to use the type of events discovered by ALICE where coherent J/ψ production happens in a peripheral Pb–Pb collision [19]. The impact parameter range covered in this measurements is clearly different to that of UPC collisions. A first extraction of both contributions was performed in [20], where the γPb cross section was determined up to an energy of 470 GeV. It is observed that data at this energy would be below a simple power law extrapolation from data at lower energies. This observation is intriguing, but not yet conclusive due to the current experimental uncertainties. ALICE has already presented preliminary results for these type of measurements using Run 2 data [21], which promises smaller uncertainties and the possibility of cross checking the procedure through measurements at mid-rapidity.

Another option to select different ranges in impact parameter is to use UPC where some neutrons are detected at beam rapidities. These neutrons originate from independent electromagnetic interactions of the same colliding nuclei that produced the J/ψ [22]. By measuring at a given rapidity the coherent UPC cross section to produce a vector meson in classes of neutron activity at beam rapidities, it is possible to disentangle both contributions [18]. Such measurements are currently underway in ALICE for the case of ρ^0 and J/ψ production.

3. Photon induced processes as a potential probe of QGP

Photon-induced interactions at heavy-ion colliders can also be used as potential probes of the quark-gluon plasma (QGP) expected to be created in the most central collision at RHIC and the LHC. STAR has presented a very interesting measurement of the production of electron-positron pairs from photon–photon interactions in Au–Au and UU collisions [23]. They compare the measurement to model predictions that include a strong magnetic field expected to be created in the initial steps of the QGP creation [24] finding that the agreement of model and data improves when adding this ingredient. These comparisons have to be taken with care, because there still are many details to be settled and other explanations, without such extreme fields, also reproduced the data, e.g. [25].

A similar type of measurement was performed by ATLAS [26]. In this case, the produced leptons were muons and the figure of merit used to assess the potential influence of the created medium on this pair was the angular asymmetry in the azimuthal plane between the directions of the muon and the ant-imuon. This asymmetry was translated into a broadening of the transverse momentum and it was hypothesised that this was due to several small momentum transfers received by the muons as they transversed the medium.

These measurements are not yet definitive, but have open the door to a new set of observables to study the properties of the quark-gluon plasma. It is expected that in the future Run 3 and Run 4 at the LHC these kind of observables will reach their maturity and contribute to our understanding of this phase of matter.

4. The structure of protons at low x

As shown schematically in Fig. 1, the computation of vector meson production has to include a piece describing the formation of the vector meson. This requires a non-perturbative model of their wave function. Recently, a new set of wave functions including spin rotation effects has been

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presented in [27, 28]. These effects turn out to be large for the case of 2S and 3S states, so it is important to study quarkonium excited states in as much detail as possible.

ZEUS [29] has measured the ratio of $\psi(2S)$ to J/ψ cross sections for exclusive photoproduction in the energy range from around 55 to 155 GeV in the γp centre-of-mass system. The measurements were based on the detection of charmonia through the decay into a pair of muons. These vector mesons have also been studied by LHCb using UPC of protons [30]. In this case, as mentioned above for UPC in heavy-ion collisions, there are also two contributions, but up-to-now there is no known way how to disentangle them, so the conversion of the LHCb measurements to the γp level include some model dependence.

Another interesting measurement involving charmonia, in this case the exclusive production of J/ψ in p–Pb collisions, was performed by ALICE [31]. They used three different topologies to cover in a continuous way the evolution in centre-of-mass energy in the γp frame from 20 to 700 GeV. One of the topologies involves measuring one of the muons from the decay of the J/ψ in the central barrel of the detector, while the second muon was measured in the forward muon spectrometer. This topology, allow ALICE to measure rapidity ranges where they do not have nominal detector coverage. The importance of measuring this process, with respect to the measurements in pp collisions, is that in the p–Pb case it is clear that the Pb is the source of the photons, so there is no ambiguity about this part of the process.

Several recent results have also been obtained for the case of ρ^0 production at HERA and at the LHC. CMS has reported the measurement of exclusive production in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV [32]. Their measurements cover the γp energy interval from 30 to 210 GeV, covering and extending the range previously measured at HERA. Where available, measurements from CMS and HERA agree with each other. CMS also presented the cross section as a function of $|t|$ at four different energies. They compare the slope with expectations from STARlight and found that the measurement falls faster than the predictions. CMS measurements are consistent with those from HERA, but there seems to be a discrepancy at values of $|t| > 0.5$ GeV^2.

H1 has also reported on new preliminary measurements [33], not only on the exclusive production of ρ^0 off protons, but also on the dissociative production. The new measurements cover the energy range from 20 to 80 GeV in the γp centre-of-mass frame. In addition to the measurement for ρ^0 they also present cross sections for the full $\pi^+\pi^-$ system and for the non-resonant contribution. The ρ^0 measurements agree with previous HERA results as well as the CMS data mentioned in the preceding paragraph.

Of special interest is the H1 measurement of the dissociative cross section for ρ^0 photoproduction off protons [34]. This type of process will be discussed in the next section. What is interesting is that the cross section seems to decrease with energy as shown in Fig. 3. This behaviour was predicted within the energy-dependent hot-spot model [14, 35] and comes about due to the saturation of the proton structure in the impact-parameter plane.

5. Dissociation: a new window to saturation at future EIC?

In a Good-Walker approach [37, 38] the cross sections for exclusive and dissociative production of vector mesons can be written in terms of the fluctuations of the fields involved in the interactions. It turns out that the main contribution comes from geometrical fluctuations in the

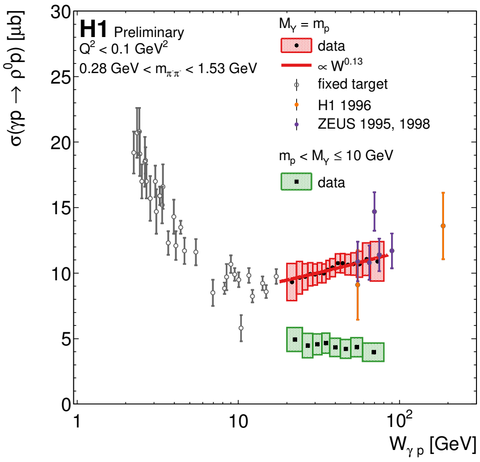

Figure 3: Preliminary cross section for the exclusive (red) and dissociative photoproduction of ρ^0 off protons as measured by H1. Figure taken from [34].

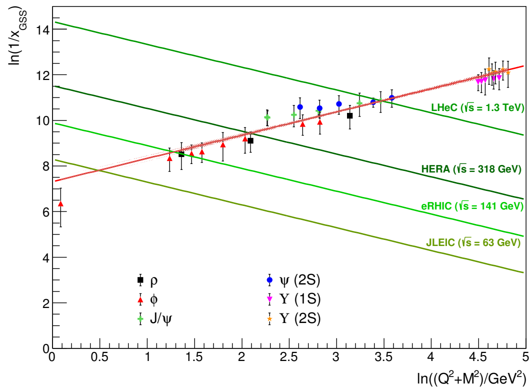

Figure 4: Energy dependence of the so-called geometrical saturation scale, that is the sacle where saturation sets in in the impact-parameter plane as a function of the scale of vector meson production as extracted from the maximum of the dissociative cross section for different vector mesons. Figure taken from [36].

impact-parameter plane [39, 40], where the fluctuations referred to the position of so-called hot spots, that is regions of high-gluon density, inside the proton.

In a model where the number of hot spots grows with energy [14] a remarkable phenomenon occurs: the cross section grows with energy, reaches a maximum and then steeply decreases. This is explained as follows: the dissociative cross section is related to the variance of the different geometrical configurations of hot spots. Once the transverse plane is filled up, all configurations look the same and the variance decreases. The position of the maximum signals then the start of saturation in the impact-parameter plane, something called the geometric-saturation scale [36].

In [36] it was discovered that the position of the maximum depends on the scale of the processes, given by the quadratic sum of the mass of the vector meson and the virtuality of the photon. This remarkable property is shown in Fig. 4. The figure also shows the kinematic reach of different past and future facilities and demonstrate that the measurement of this process could map the energy dependence of this saturation scale in a future EIC.

6. Conclusions and outlook

As shown in the preceding sections, photon-induced processes are a very good tool to study the high-energy limit of QCD. This field is quite active due to the many new experimental results from the HERA, RHIC and LHC facilities and the promise of many new results to come in the near future with already existing data or data from the Run 3 and Run 4 at the LHC [41]. In parallel, several new groups are quite active in theory and phenomenology. These results have not been discussed in this contribution, but can be found in these proceedings.

Photon-induced processes are not only used to study the high energy limit of QCD, but they are being introduced as tools to investigate the properties of the QGP. This is a budding field and Run 3 and Run 4 at the LHC, as well as results from RHIC should help it to mature in the next few years.

Finally, most of the measurements related to photon-induced process discussed in this contribution have been made at the RHIC and LHC facilities, which were designed to measure a completely different type of physics. Nonetheless, the ingenuity of the experimentalists have made it possible to obtain very good results. Imagine what this same ingenuity would achieve if applied at a facility specifically designed to study this kind of physics! The EIC, in whatever of their manifestations, it is eagerly awaited!

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