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Exclusive $J/\psi, \rho, \phi$ and Υ production at HERA and LHC within dipole models

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Abstract. We describe exclusive $J/\psi, \rho, \phi$ and Υ production at HERA and calculate cross sections and transverse momentum distributions for the incoherent diffractive production of vector mesons J/ψ and Υ on heavy nuclei. Within the color dipole approach, we derive the multiple scattering expansion of the incoherent diffractive cross section as an expansion over quasielastic scatterings of the color dipole. We compare our results to the measurement of the ALICE (LHC) collaboration for incoherent J/ψ production

1 Introduction

A precise knowledge of the partonic structure of the proton and of parton density functions (PDFs) is essential in order to access fully the physics potential of LHC and RHIC. The main physics goal of LHC is to find how to complete or extend the Standard Model. One of the most promising ways to this is the precise investigation of the Higgs boson production, ie. of the Higgs boson decays and its production cross section. Any deviation of the measured Higgs cross section from its predicted value is a sign of the physics beyond the Standard Model (BSM).

A precise understanding of QCD evolution is also important in other areas of science, in the investigation of the high density gluonic fields at RHIC and LHC and in cosmic ray physic.

The first evidence for partonic structure of the nucleon was observed in electron-proton DIS experiments at SLAC in 1966. Since then a lot of effort has been put in measuring DIS processes and in extracting PDFs from the data. In doing so one applied the DGLAP evolution first in leading order (LO) then in next to leading (NLO) and next to next to leading order (NNLO). Also different schemes to treat the contributions of the heavy quark masses were developed. In addition various resummation techniques were applied. All these gave until recently a very good description of HERA inclusive DIS cross sections and LHC Drell-Yan process data although the predictions for e.g. Higgs cross section using various fitting schemes are differing by about 10%. This is sizably more than the expected BSM effects could be.

On the other hand the DGLAP evolution is theoretically only well motivated in the region of large Bjorken x. However, the HERA data extend substantially into the region of low-x. This region determines also, to large extent, the Higgs cross sections at LHC. Therefore it was since longer time quite puzzling why DGLAP evolution provided (until recently) such a good description of data. The fact that DGLAP evolution could not be the right scheme was only visible in the exclusive processes.

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For example, one observed abundant particle and forward jets production in HERA DIS processes in contradiction with the pure DGLAP expectations, resulting from the strong ordering of parton emissions.

This was the situation until the spring of this year. At the DIS conference in Warsaw the final, most precise HERA data were presented, which are based on much higher statistics (factor five increase) than the previous ones [1]. This data allowed for a much better evaluation of systematic errors, which lead to a substantial improvement of precision. Simultaneously the HERAfitter group presented a full evaluation of the new data using the standard DIS techniques. According to this evaluation the $\chi^2/N_{dof} \approx 1.25$ for data with $Q^2 > 3.5$ GeV^2. Since N_{dof} is about 1350 the fit probability is very low, around 10^{-8}. The increase of the Q^2 cut improves the fit but not substantially, the probability remains very low. In addition, with lower Q^2 cuts the NLO evaluation is providing the better χ^2's than the NNLO evaluation. In the past the χ^2/N_{dof}'s were always close to one which gave very good fit probabilities.

In view of this situation the impact of this project will lay on isolating and understanding of the sources of deviations from the usual DGLAP PDF fit techniques. To do so I will use the normal PDF fits supplemented with the higher twist corrections. To understand the possible pattern of higher twists I will simultaneously fit the data with the dipole models, starting first with the BGK model. The connection between dipole model and higher twist approach was worked out in the papers by Bartels, Golec Biernat and Peters [2] and Bartels, Golec Biernat and Motyka [3]. If the higher twist method will give a substantial improvement I will extend this investigation to the investigation of saturation effects at higher scales. In case that higher twist corrections would not lead to a substantial improvement other methods like for example special modifications of splitting functions could also be considered. The leading experts in the field, Jochen Bartels, Henri Kowalski, Krzysztof Golec-Biernat and Leszek Motyka agreed to collaborate with me on this subject.

Of special interest are also data on exclusive J/ψ production at LHC [4]. In this measurement one is sensitive to the $\gamma p \to J/\psi p$ amplitude at γp cms-energies in the TeV region, which is far beyond the HERA regime. As follows from the work of Martin, Teubner, Ryskin [5] and Kowalski, Teaney [6] and Kowalski, Motyka and Watt [7], this process allows the determination of the gluon density down to very low $x < 10^{-6}$. The simultaneous analysis of this process together with the analysis of the most precise HERA data and the LHC Drell-Yan processes is very promising because it may allow to understand the saturation effects (or its absence) at larger scales. This analysis is possible only now through the HERAfitter platform.

In the second part of the project I will concentrate on the study of transverse gluonic structures of the nucleus and nuclei. They are described by two models called: IPsat [6] or bSat[7], which take into account the transverse structure of the gluon distribution by adding the impact parameter dependence to the BGK model.

I will concentrate on the measurement of exclusive J/ψ vector meson photoproduction at RHIC and the LHC. The J/ψ meson is a best probe to investigate a structure of nuclei because it interacts with nucleon via gluons and not photons as in the case of electrons. The J/ψ meson is a bound state of a charm quark-antiquark pair and therefore the corresponding dipole is naturally small. The cross section is relatively high because we will consider the photoproduction. It is important to know that in nuclei, the small charmed dipole presumably scatters on individual nucleons. Despite the high energies involved, the nucleus will frequently remain intact because the large absorption cross section together with the optical theorem assures that the scattering process has to be coherent in about 15 % of cases [8, 9]. Because the charmed quark dipole interacts almost completely via two-gluon exchange with matter, the deflection of J/ψ measures directly the intensity and the spatial distribution of the strong field that keeps the nucleus together.

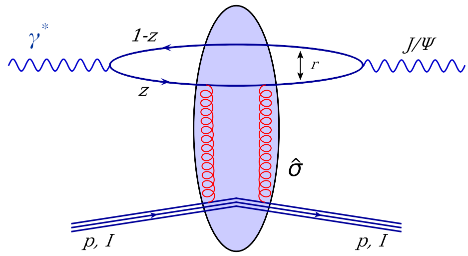

Figure 1. *Elastic scattering of J/ψ meson on a proton or ion in the dipole representation*

This allow to see precisely the structure of gluonic fields, which has never been seen before. In the Fig.2 elastic scattering of J/ψ meson is shown.

In particular, presently exists new, precise HERA data on the exclusive J/ψ and ρ production, which should be analyzed within the dipole models : IPsat or the bSat. IPsat model is describing the diffractive, exclusive J/ψ production, the bSat model is extending this description to the exclusive ρ and ϕ production. The main properties of the gluon transverse distribution in a proton can be determined from the t-distributions of the J/ψ and ρ mesons measued at HERA. This data indicate that the transverse gluon shape observed in the various exclusive processes is compatible with the same proton-gluon distribution, i.e. it is independent of a specific projectile, J/ψ, ρ or ϕ [10].
It will be very interesting to extend these investigations to nuclei. Presently RHIC and the LHC [11], [12] are collecting data on heavy ion-ion and heavy ion-proton scattering. The experiments observe the diffractive, exclusive J/ψ and ρ production, which is described by a very similar dipole formation as in the electro-production at HERA [13],[6], [14].
The STAR experiment presented at the EDS Blois 2013 conference [11] preliminary data on exclusive ρ production which show a clear dip structure. This dip structure was extensively discussed in [14] where it was shown that it is directly connected with the radius of nucleus (on which the scattering takes place) and also with the so called skin depth and the degree of coherence. It will be very interesting to make predictions from the above dipole models to better know the gluonic structure of nuclei.

These studies are very important and unique because after almost 80 years of investigations of nuclear structure some of the basic properties are still so poorly understood, because of the lack of proper tools to explore nuclei.

Finally let us turn to the subject of saturation.
One of the main results of HERA is the observation that the gluon density increases quickly with decreasing x. This suggests that at some small x the dipole could undergo multiple interactions. The degree of saturation is characterized by the size of the dipole r_S which, at a given x, starts to interact multiple times. The dipole size r_S is defined, by convention [10], via the relation[1]

$$\frac{d\sigma_{q\bar{q}}(x, r_S, b)}{d^2b} = 2(1 - \exp(-1/2)) \approx 0.8. \tag{1}$$

The saturation scale is defined then as $Q_S^2 = 2/r_S^2$ and is a function of x. A high value of the saturation scale means that gluon density is so high that even small dipoles interact many times.

In various analyses of HERA data the saturation scale, in the proton center, was found to be $Q_S^2 \approx 0.5$ GeV^2 at $x \approx 10^{-3}$. At LHC the exclusive J/ψ production is observed up to $x \approx 10^{-6}$,

[1]From the unitarity limit the highest value of a dipole cross section is $d\sigma/d^2b = 2$.

therefore the saturation scale could reach $Q_S^2 \approx 2$ GeV^2 [10]. Such a substantial increase of scale should be visible in data.

The saturation effects will also be seen in nuclei through the measurement of the absolute value of cross sections. The dipole model predicts these values precisely provided the scattering takes place on nucleons within the nucleus which have the same properties as free protons. Any deviation from the expected value carries information about nuclear or saturation effects. For example, the total dipole proton cross section, σ_p, can be different for a nucleon in a nucleus than for a proton because a nucleon within a nucleus can have a different size than a free proton or neutron. This would change sizably the value of the nuclear dipole cross section and therefore also the values of the observed diffractive cross sections. By the same argument the measurement of F_2 on nuclei is also determined by the nuclear properties and will lead to very interesting saturation effects as discussed in [6, 9]. Saturation is dependent on the size of the scattering objects, therefore its measurement and the absolute value of the cross section could indicate on what objects the scattering takes place.

2 Dipole models

The dipole picture was first derived, in the low x limit of QCD, by Nikolaev and Zaharov [15]. They have shown that the deep inelastic scattering can be viewed as a two stage process; first the virtual photon fluctuates into a dipole, which consists of a quark-antiquark pair (or a $q\bar{q}g$ or $q\bar{q}gg$ ... system) and in the second stage the dipole interacts with the proton. Dipole denotes a quasi-stable quantum mechanical state, which has a very long life time ($\approx 1/m_p x$) and a size r, which remains unchanged during scattering. The wave function Ψ determines the probability to find a dipole of size r within a photon. This probability depends on the value of external Q^2 and the fraction of the photon momentum carried by the quarks forming the dipole, z. Neglecting the z dependence, in a very rough approximathion, $Q^2 \sim 1/r^2$.

The scattering amplitude is a product of the virtual photon wave function, Ψ, with the dipole cross section, $\sigma_{\rm dip}$, which determines a probability of the dipole-proton scattering. Thus, within the dipole formulation of the $\gamma^* p$ scattering

$$\sigma_{T,L}^{\gamma^* p}(x, Q^2) = \int dr^2 \int dz \Psi^*_{T,L}(Q, r, z) \sigma_{\rm dip}(x, r) \Psi_{T,L}(Q, r, z), \tag{2}$$

where T, L denotes the virtual photon polarization and $\sigma_{T,L}^{\gamma^* p}$ the total inclusive DIS cross section.

This simple and intuitive approach became then a basis of many dipole many models, [16–21]. which have been developed to test various aspects of data. They vary due to different assumption made about the physical behavior of dipole cross sections. In the following we will shortly review some them to motivate the choice of the model used for present investigation.

2.1 BGK model

The evolution ansatz of the GBW model was improved in the model proposed by Bartels, Golec-Biernat and Kowalski, (BGK) [23], by taking into account the DGLAP evolution of the gluon density in an explicit way. The model preserves the GBW eikonal approximation to saturation and thus the dipole cross section is given by

$$\sigma_{\rm dip}(x, r^2) = \sigma_0 \left(1 - \exp\left[-\frac{\pi^2 r^2 \alpha_s(\mu^2) x g(x, \mu^2)}{3\sigma_0}\right]\right). \tag{3}$$

The evolution scale μ^2 is connected to the size of the dipole by $\mu^2 = C/r^2 + \mu_0^2$. This assumption allows to treat consistently the contributions of large dipoles without making the strong coupling constant, $\alpha_s(\mu^2)$, un-physically large. This means also that we can extend the model, keeping its perturbative character, to the data at low Q^2, because the external Q^2 and the internal μ^2 scales are connected only by the wave function.

The gluon density, which is parametrized at the starting scale μ_0^2, is evolved to larger scales, μ^2, using LO or NLO DGLAP evolution. We consider here two forms of the gluon density:

- the *soft* ansatz, as used in the original BGK model

$$xg(x, \mu_0^2) = A_g x^{-\lambda_g} (1 - x)^{C_g}, \tag{4}$$

- the *soft* + *hard* ansatz

$$xg(x, \mu_0^2) = A_g x^{-\lambda_g} (1 - x)^{C_g} (1 + D_g x + E_g x^2), \tag{5}$$

The free parameters for this model are σ_0 and the parameters for gluon A_g, λ_g, C_g or additionally D_g, E_g, Their values are obtained by a fit to the data. The fit results were found to be independent on the parameter C, which was therefore fixed as $C = 4$ GeV^2, in agreement with the original BGK fits. It is also possible to vary the parameter μ_0^2. However, to assure that the evolution is performed in the perturbative region and to be compatible with the standard pdf fits we took as a starting scale $\mu_0^2 = 1.9$ or 1.1 GeV^2. In the BGK model, the μ_0^2 scale is the same as the Q_0^2 scale of the standard QCD pdf fits.

3 Incoherent diffractive photoproduction of J/ψ and Υ on heavy nuclei at the LHC in the color dipole approach

Within the color dipole approach, we derive the multiple scattering expansion of the incoherent diffractive cross section as an expansion over quasielastic scatterings of the color dipole. We also compare our results to the measurement of the ALICE collaboration for incoherent J/ψ production at $\sqrt{s_{NN}} = 2.76$ TeV and show predictions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV.

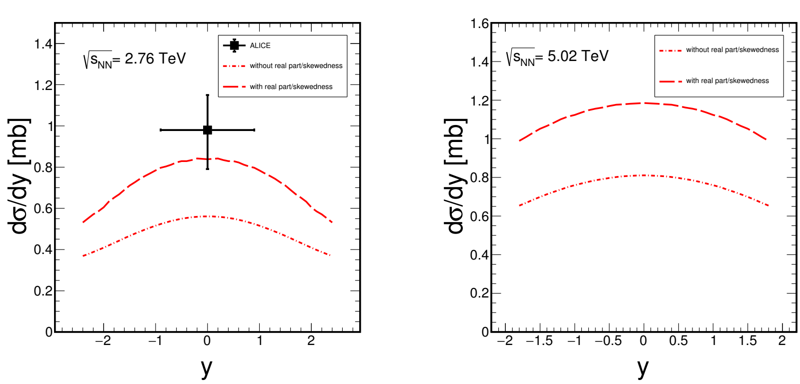

Figure 2. Incoherent diffractive cross section for $\gamma A \to J/\psi X$ for $A =^{65}$ Cu at $W = 31$ GeV (upper panel) and $W = 100$ GeV. Shown are the contributions from 1 to 5 scatterings. Here the nuclear absorption was not taken into account.

In Figure 2 we show predictions for the LHC using the gluon density obtained from fits with saturation ansatz of Tables [24]. We see that there is a large discrepancy between ATLAS data for jets and predictions from BGK dipole model. Our calculations are in agreement with data from ALICE in ultraperipheral lead-lead collisions at $\sqrt{s_{\rm NN}} = 2.76\,\text{TeV}$. There seems to be little room left for contributions with nucleon dissociation. It will be interesting in the future to calculate also these contributions, e.g. from the model presented in [25] in order to be able to predict the transverse momentum spectra of vector mesons in the whole experimentally accessible phase space.

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