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Incoherent J/ψ production at large $|t|$ identifies the onset of saturation at the LHC

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The study of incoherent production of a vector meson in diffractive processes provides information about the inner composition of the target hadron at the partonic level. The incoherent cross section is sensitivite to fluctuations in the configuration of the color field of the target. The energy-dependent hot-spot model, based on the color dipole approach, incorporates subnucleon degrees of freedom known as hot spots. These hot spots represent regions of high gluonic density, and their positions fluctuate event-by-event. As the collision energy increases, an intense concentration of gluons within hadrons occurs, leading to a transition from a dilute to a saturated regime. To investigate this phenomenon, we propose studying the energy dependance of incoherent photo-production of vector mesons in diffractive processes at various values of the Mandelstam-t variable. The $|t|$ distribution is related to fluctuations of different transverse sizes. The coherent cross section is sensitive to nuclear sizes, while incoherent processes are sensitive to both nucleon and hot spot sizes. We predict that the onset of saturation can be determined at the LHC by measuring the energy dependence of the incoherent J/ψ photo-production cross section at large $|t|$, a region dominated by hot spot contributions.

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1. Introduction

The study of quantum chromodynamics (QCD) in the high-energy regime predicts the existence of saturation—a state, where the density of gluons inside hadrons becomes so high that they start to interact with each other. To identify signatures of saturation, one needs to focus on processes sensitive to the partonic structure of the target, such as diffractive vector meson production. In previous studies [1, 2], we predicted the energy dependence of incoherent J/ψ photo-production off protons, correctly reproducing the rise of the cross section with $W_{\gamma\mathrm{p}}$ as measured at HERA [3]. Our calculations suggest that the cross section reaches a maximum at $W_{\gamma\mathrm{p}} \approx 500$ GeV, followed by a steep decrease at higher energies, providing a signature of gluon saturation.

This contribution reviews the predictions of the energy-dependent hot-spot model for the photo-production of J/ψ off lead (Pb) in diffractive interactions.

2. Energy dependent hot-spot model

In a Good-Walker approach the coherent cross section for the diffractive photo-production of a vector meson V off a target H is calculated as an average over the different configurations of the target

$$\left.\frac{\mathrm{d}\sigma^{\gamma^* \mathrm{H}\to\mathrm{VH}}}{\mathrm{d}|t|}\right|_{\mathrm{T,L}} = \frac{\left(R_g^{\mathrm{T,L}}\right)^2}{16\pi} |\langle \mathcal{A}_{\mathrm{T,L}} \rangle|^2, \tag{1}$$

while dissociative processes, measure the variance over the configurations

$$\left.\frac{\mathrm{d}\sigma^{\gamma^* H\to\mathrm{V}Y}}{\mathrm{d}|t|}\right|_{\mathrm{T,L}} = \frac{\left(R_g^{T,L}\right)^2}{16\pi} \left(\langle |\mathcal{A}_{\mathrm{T,L}}|^2 \rangle - |\langle \mathcal{A}_{\mathrm{T,L}} \rangle|^2\right), \tag{2}$$

where $\mathcal{A}_{\mathrm{T,L}}$ is the scattering amplitude (for details see e.g [2]), T and L denote transverse and longitudinal polarization respectively. The factor $R_g^{\mathrm{T,L}}$ is called the skewedness correction [4]. The centre-of-mass energy per nucleon of the photon–target system (W) is related to Bjorken-x through $x = (Q^2 + M^2)/(Q^2 + W^2)$, where M is the mass of the vector meson.

The cross section for the interaction, at an impact parameter $\vec{b}$, of a dipole of transverse size $\vec{r}$ with the proton is

$$\frac{\mathrm{d}\sigma_{\mathrm{p}}^{\mathrm{dip}}}{\mathrm{d}\vec{b}} = \sigma_0 N(x,r) T_{\mathrm{p}}(\vec{b}), \tag{3}$$

while for Pb, the dipole cross section reads

$$\left(\frac{\mathrm{d}\sigma_{\mathrm{Pb}}^{\mathrm{dip}}}{\mathrm{d}\vec{b}}\right) = 2\left[1 - \left(1 - \frac{1}{2A}\sigma_0 N(x,r) T_{\mathrm{Pb}}(\vec{b})\right)^A\right] \tag{4}$$

with $A = 208$.

The fluctuations of the target are implemented in the profile functions. The proton profile is determined by summing the individual hot spot profiles over the total number of hot spots:

$$T_{\mathrm{p}}(\vec{b}) = \frac{1}{N_{\mathrm{hs}}} \sum_{i=1}^{N_{\mathrm{hs}}} T_{\mathrm{hs}}\left(\vec{b} - \vec{b}_i\right), \quad \text{with} \quad T_{\mathrm{hs}}\left(\vec{b} - \vec{b}_i\right) = \frac{1}{2\pi B_{\mathrm{hs}}} \exp\left(-\frac{\left(\vec{b} - \vec{b}_i\right)^2}{2B_{\mathrm{hs}}}\right). \tag{5}$$

The positions of hot spots are sampled from a two-dimensional Gaussian distribution centered at the origin, with the width B_{p}.

In the Pb case, the profile function is given by

$$T_{\text{hs}}(\vec{b}-\vec{b}_i) = \frac{1}{2\pi B_{\text{hs}}} \sum_{i=1}^{A=208} \frac{1}{N_{\text{hs}}} \sum_{j=1}^{N_{\text{hs}}} \exp\left(-\frac{\left(\vec{b}-\vec{b}_i-\vec{b}_j\right)^2}{2B_{\text{hs}}}\right), \tag{6}$$

where, the positions of nucleons are sampled from a nuclear thickness function utilizing a Woods-Saxon distribution.

The key feature of our model is the evolution of the number of hot spots with energy, ensured by N_{hs} increasing with decreasing x. This is shown schematically in Figure 1. N_{hs} is sampled from a zero-truncated Poisson distribution, where the Poisson distribution has a mean value

$$\langle N_{hs}(x)\rangle = p_0 x^{p_1}(1+p_2\sqrt{x}). \tag{7}$$

The parameters of the model are specified in [2].

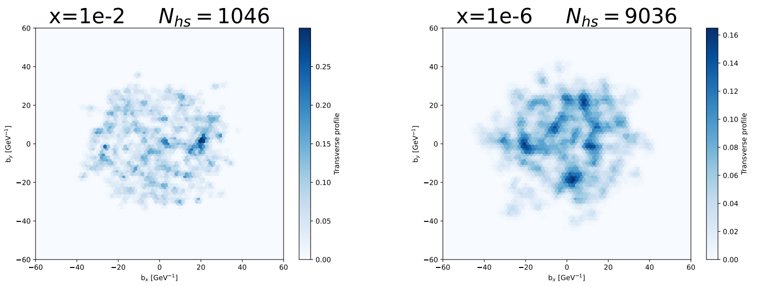

Figure 1: Transverse profile of a lead nucleus generated using the hot-spot model for different values of Bjorken-x: $x = 10^{-2}$ **(left)**, $x = 10^{-6}$ **(right)** .

3. Results

Utilizing the model described above, we compute the cross sections for both coherent and incoherent J/ψ photo-production off Pb and compare our predictions to LHC data. Results for the proton target are thoroughly discussed in our previous publications [1, 2].

As shown in Figure 2 (left panel), our model successfully reproduces the energy dependence of coherent production off Pb over nearly two orders of magnitude in W covered by the J/ψ data. Figure 2 (right panel) illustrates the Mandelstam-t dependence. While our model accurately describes the behavior of the incoherent cross section within current experimental errors, it exhibits a steeper slope compared to the data on coherent production. Thus, the latter data seems to indicate a Pb ion slightly larger than assumed in the theoretical predictions. This phenomenon is not included in our model due to a lack of well-established experimental data at other energies in order to model it. Nonetheless the effect is small, and would not affect the qualitative conclusions of our work.

Our main result is shown in Figure 3. Prediction of the energy-dependent hot-spot model for the incoherent photo-production of J/ψ vector mesons off Pb for different values of the Mandelstam-t

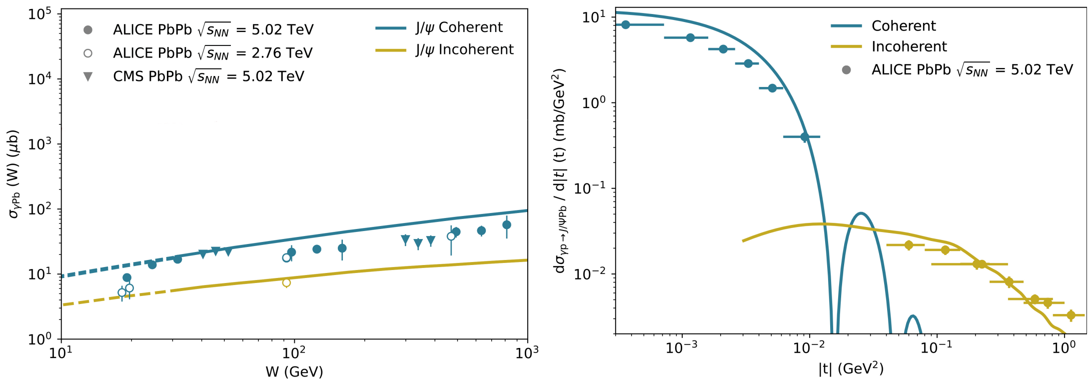

Figure 2: **(left)** Coherent (blue) and incoherent (gold) production of J/ψ off Pb as a function of W. **(right)** Mandelstam-t dependence of J/ψ photo-production off Pb at an energy W = 125 GeV. The markers show data from the ALICE [5–7] and CMS [8] collaborations at the LHC, while the lines depict the predictions of our model.

variable, which is related through a Fourier transform to the distribution of matter in the impact-parameter plane. Scanning the energy behaviour in specific $|t|$ ranges samples fluctuations of different transverse sizes and allows for the isolation of the contribution of hot spots where one expects saturation effects to set in. For small $|t|$ values, the cross section raises with energy, however at $|t|$ = 1 GeV^2 the rise of the cross section reaches a maximum at around W = 297 GeV and then decreases.

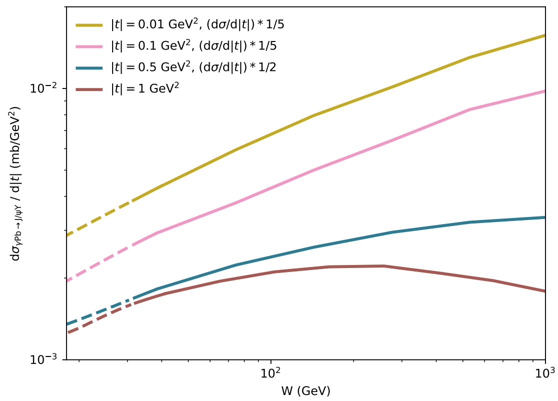

Figure 3: The energy dependance of the incoherent photo-production of J/ψ off Pb in diffractive interactions. The lines depict the energy dependence of this process at different values of the Mandelstam-t variable. Some of the lines have been scaled to improve the readability of the figure.

4. Summary

Based on our predictions, properly bench-marked with experimental data, we predict that the onset of saturation can be measured by the energy dependence of the cross section for incoherent J/ψ photo-production at large $|t|$ using ultra-peripheral Pb–Pb collisions at the LHC.

Acknowledgements

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