SATURATION WITHIN THE REACH OF THE LHC: INCOHERENT J/ψ PRODUCTION AT LARGE $|t|$*

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We identify a new way of pinpointing the presence of saturation effects in the LHC data by looking at incoherent J/ψ production at large $|t|$. We use an energy-dependent hot spot model to show that saturation effects are manifested through a fall-off of the incoherent vector-meson production cross section. This fall-off comes from the reduced variance of possible target configurations due to parton overlap at Mandelstam-t scales, where individual hot spots become important.

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1. Introduction

At high energies corresponding to small Bjorken-x, hadrons in hard interactions transition from a dilute to a saturated regime in perturbative QCD, reaching a dynamic equilibrium [1, 2]. HERA measurements [3] show that gluons dominate the proton structure at small x, prompting the use of gluon-sensitive observables like diffractive photo-production of vector mesons [4] to search for saturation effects. In the colour dipole picture [5], this process factorises into photon splitting, dipole–hadron interaction, and vector-meson formation, and has been extensively studied at HERA, the LHC, and is central to future facilities such as the EIC.

We proposed a hot spot model where the number of hot spots increases with energy [6], predicting that the incoherent J/ψ production cross section off protons reaches a maximum and then decreases due to similar configurations — a percolation-like effect. This model has been extended to nuclear targets and different vector mesons [7]. Here, we identify a new observable to detect saturation at the LHC: measuring incoherent vector-meson production off nuclei as a function of energy at different Mandelstam-t values.

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Since t relates to the transverse distribution of colour charges, analysing energy behaviour in specific t ranges isolates fluctuations of different sizes, highlighting the hot spot contributions where saturation is expected. This method allows for a unique identification of saturation effects at current LHC energies. This paper is based on the work presented in [8].

2. The hot spot model formalism

The cross section for the coherent diffractive photo-production of a vector meson V off a hadron target H in the Good–Walker approach is given by

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

where the scattering amplitude can be written as

$$\mathcal{A}_{\mathrm{T,L}}\left(x,Q^2,\vec{\Delta}\right) = i\int \mathrm{d}\vec{r}\int_0^1\frac{\mathrm{d}z}{4\pi}\int\mathrm{d}\vec{b} \times|\Psi_V^*\Psi_{\gamma^*}|_{\mathrm{T,L}}\exp\left[-i\left(\vec{b}-\left(\frac{1}{2}-z\right)\vec{r}\right)\vec{\Delta}\right]\frac{\mathrm{d}\sigma_H^{\mathrm{dip}}}{\mathrm{d}\vec{b}}\,. \tag{2}$$

The variance of the scattering amplitude gives the expression for the cross section as

$$\left.\frac{\mathrm{d}\sigma^{\gamma^* p\to VY}}{\mathrm{d}|t|}\right|_{\mathrm{T,L}} = \frac{\left(R_g^{\mathrm{T,L}}\right)^2}{16\pi}\left(\langle|\mathcal{A}_{\mathrm{T,L}}|^2\rangle-|\langle\mathcal{A}_{\mathrm{T,L}}\rangle|^2\right)\,, \tag{3}$$

where T and L stand for the transverse and longitudinal contributions. For more details and all variable definitions, see [8]. The colour dipole scattering cross section for protons is given by

$$\frac{\mathrm{d}\sigma_p^{\mathrm{dip}}}{\mathrm{d}\vec{b}} = \sigma_0 N(x,r)T_p\left(\vec{b}\right)\,, \tag{4}$$

where we use the GBW model for the parametrization of the scattering amplitude [9]. The dipole cross section for the scattering with lead targets is

$$\left(\frac{\mathrm{d}\sigma_{\mathrm{Pb}}^{\mathrm{dip}}}{\mathrm{d}\vec{b}}\right) = 2\left[1-\left(1-\frac{1}{2A}\sigma_0 N(x,r)T_{\mathrm{Pb}}\left(\vec{b}\right)\right)^A\right]\,. \tag{5}$$

Proton profile $T_p(\vec{b}\,)$ is given by a sum of individual hot spots, which are approximated as having the Gaussian colour-charge density with a width of $B_{\rm hs}$ as discussed in more detail in [8]. The nuclear profile then takes the form of

$$T_{\rm Pb}\left(\vec{b}\right) = \frac{1}{2\pi B_p}\sum_{j=1}^{A=208}\exp\left(-\frac{\left(\vec{b}-\vec{b}_j\right)^2}{2B_p}\right), \tag{6}$$

where the sum goes over all nucleons in Pb, with their positions sampled from an integrated Woods–Saxon distribution. Thus, the hot spot profile is given by

$$T_{\rm hs}\left(\vec{b}-\vec{b}_i\right) = \frac{1}{2\pi B_{\rm hs}}\sum_{i=1}^{A=208}\frac{1}{N_{\rm hs}}\sum_{j=1}^{N_{\rm hs}}\exp\left(-\frac{\left(\vec{b}-\vec{b}_i-\vec{b}_j\right)^2}{2B_{\rm hs}}\right). \tag{7}$$

3. Results

In this section, we present the results of our simulation. Figure 1 shows the J/ψ and ρ production off protons for both coherent and incoherent interactions dependent on the energy of the interaction, while Fig. 2 focuses on vector-meson production off nuclei. Both figures aim to validate the model and highlight its ability to accurately describe the available data.

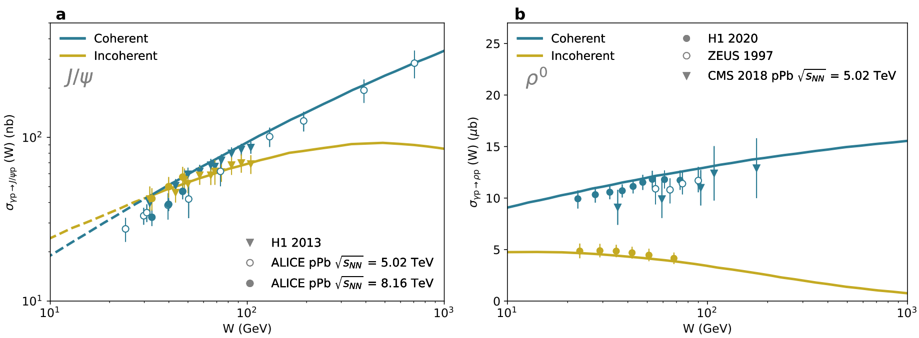

Fig. 1. Diffractive photo-production of J/ψ (a) and ρ^0 (b) off protons for the coherent (blue) and incoherent (gold) processes. The markers show measured data from the H1 [10, 11], ALICE [12–14], and CMS [15] collaborations, while the lines depict the predictions of our model. The dashed line represents values of W that correspond to x greater than 0.01, where the validity of the formalism is questionable. Figure taken from [8].

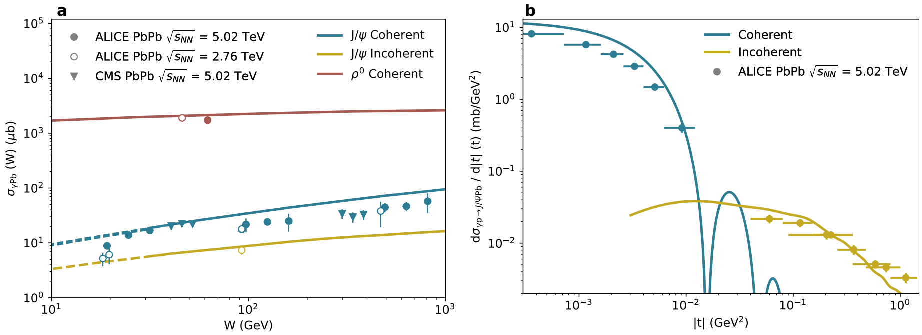

Fig. 2. (a) Energy dependence of ρ^0 and J/ψ photo-production off Pb. (b) Mandelstam-t dependence of coherent (blue) and incoherent (gold) J/ψ photo-production off Pb at an energy $W \approx 125$ GeV. The markers show data from the ALICE [16–20] and CMS [21] collaborations at the LHC, while the lines depict the predictions of our model. Figure taken from [8].

The identification of a new variable able to probe saturation effects at the LHC is presented in Fig. 3. There, we can see that incoherent production of the J/ψ vector meson off nuclei at large values of Mandelstam-t starts to decrease — a manifestation of the reduced variance of the saturated target. The origin of this effect is discussed in detail [8].

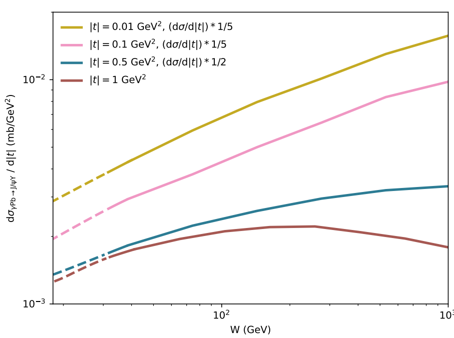

Fig. 3. Prediction of the energy-dependent hot spot model for the incoherent photo-production of J/ψ vector mesons off Pb in diffractive interactions. The lines depict the energy dependence of this process at different values of the Mandelstam-t variable. Some of the lines have been scaled to improve the readability of the figure. Figure taken from [8].

4. Summary and outlook

Building on the energy-dependent hot spot model validated with HERA and LHC data, we propose to detect the onset of saturation through the incoherent J/ψ photo-production at large Mandelstam-t. In this high-t region, individual hot spots are resolved, and their saturation manifested by a decreased variation of the scattering amplitude resulting in a suppression of the incoherent cross section. Our prediction is that saturation effects can be observed using ultra-peripheral Pb–Pb collisions at the LHC.

This measurement can be performed using data collected during LHC Run 2 (2015–2018). Additionally, the LHC began its Run 3 Pb–Pb data collection in 2023, with more data expected during Runs 3 and 4. We anticipate approximately one million J/ψ events in the $\mu^+\mu^-$ channel [22]. This dataset should enable us to measure the process with low uncertainties enabling us to pinpoint the onset of the elusive saturation effects.

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