Saturation effects in high-energy evolution for exclusive heavy vector meson production

Jani Penttala[1]

In collaboration with Christophe Royon[2]

[1]University of California, Los Angeles

SURGE collaboration

[2] University of Kansas

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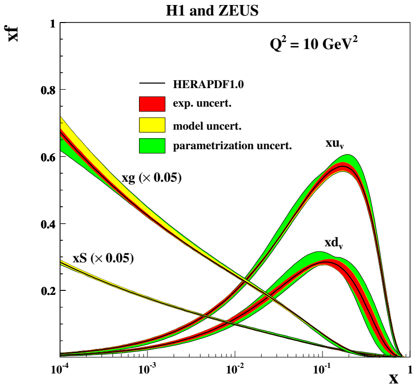
Gluon saturation at high energy

- HERA: rapid growth of gluon distribution at small x
- Growth cannot go on indefinitely: violation of unitarity
- Will eventually be tamed by gluon recombination effects
- Prediction from theory: **gluon saturation**
- Signs of saturation in the experimental data but no definite evidence
- Important to understand effects of saturation
  – Motivation to compare linear (no saturation) and nonlinear (saturation) models



H1 and ZEUS, 0911.0884

Exclusive vector meson production as a probe for saturation

- Main process: $\gamma^* + A \to V + A$

  where $V = \rho,\ \phi,\ \mathrm{J}/\psi,\ \Upsilon\ \ldots$

- Ryskin, Z.Phys.C 57 (1993) 89-92:

$$\frac{\mathrm{d}}{\mathrm{d}t}\sigma(\gamma^* + A \to V + A) \sim [xg(x)]^2$$

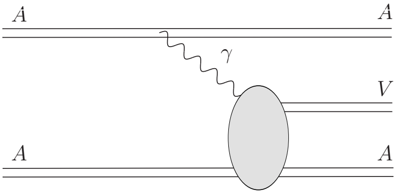
  $\Rightarrow$ Very sensitive to the gluon structure of the target!

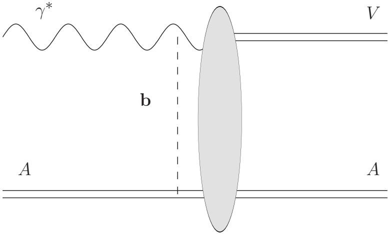
- Exclusive process:

  The momentum transfer $\mathbf{\Delta}$ can be measured

  - Conjugate of the impact parameter $\mathbf{b}$

    $\Rightarrow$ Measures spatial distribution of small-x gluons





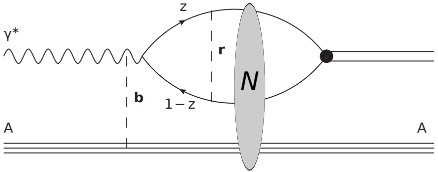
Exclusive vector meson production in the dipole picture

Factorization in the high-energy limit:

Invariant amplitude for exclusive vector meson production

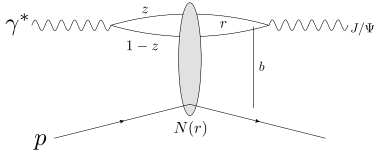
$$\operatorname{Im}\mathcal{A}_\lambda = 2\int \mathrm{d}^2\mathbf{b}\,\mathrm{d}^2\mathbf{r}\frac{\mathrm{d}z}{4\pi}e^{-i\mathbf{b}\cdot\boldsymbol{\Delta}}\Psi_{\gamma^*}^{q\bar{q}}(\mathbf{r},z)N(\mathbf{r},\mathbf{b},x)\Psi_V^{q\bar{q}*}(\mathbf{r},z), \qquad t=-\boldsymbol{\Delta}^2$$

- $\Psi_{\gamma^*}^{q\bar{q}}$: Photon light-cone wave function
- N: Dipole-target scattering amplitude
- $\Psi_V^{q\bar{q}}$: Vector meson light-cone wave function
- $x = (M_V^2 + Q^2)/W^2$
- $\operatorname{Re}\mathcal{A} \approx \operatorname{Im}\mathcal{A} \times \tan\left(\frac{\pi}{2}\delta\right)$ where $\delta = \frac{\partial}{\partial \log 1/x}\log(\operatorname{Im}\mathcal{A})$

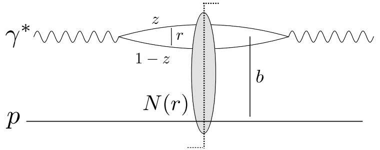


Dipole amplitude N

- Universal: appears in different processes
- A nonperturbative quantity
- But: the energy dependence is perturbative
- Initial condition $N(r, x_0) \rightarrow$ evolve to smaller x
- Two different approaches
  - linear BFKL evolution
  - nonlinear BK evolution
- Close to each other in the region where saturation effects are not important (low energy)



$$\sigma^{\gamma^* p \rightarrow Vp} \sim |\text{dipole amplitude } N|^2$$



$$\sigma^{\gamma^* p} \sim \text{dipole amplitude } N$$

BFKL evolution

- Linear evolution:

$$\frac{\partial}{\partial \log 1/x} N(\mathbf{r}, x) = \int \mathrm{d}^2\mathbf{r}' \, \mathcal{K}(\mathbf{r}, \mathbf{r}') N(\mathbf{r}', x)$$

  where the kernel $\mathcal{K}$ depends on the exact order and scheme of the BFKL used

- Leading-order BFKL equation leads to unreasonably fast energy evolution
- Need to resum collinear logarithms: $\Rightarrow$ improved energy evolution

  Salam, hep-ph/9806482, hep-ph/9910492

- Asymptotic evolution $N(\mathbf{r}, x) \sim \left(\frac{1}{x}\right)^{\omega_s} N(\mathbf{r})$ where ω_s is the largest eigenvalue of the BFKL kernel $\Rightarrow \sigma \sim W^\delta$
  - General prediction of the BFKL equation
- This work: LO BFKL + resummation (with α_s = constant)
  - Effective value $\alpha_\mathrm{s} = 0.13$ determined by matching ω_s to J/ψ production data

BK evolution

- For BK: we use leading-order BK equation

$$\frac{\partial}{\partial \log 1/x} N(\mathbf{x}_{01}) = \int \mathrm{d}^2\mathbf{x}_2\, \mathcal{K}(\mathbf{x}_{ij}) \times \left[N(\mathbf{x}_{02}) + N(\mathbf{x}_{12}) - N(\mathbf{x}_{01}) - \underbrace{N(\mathbf{x}_{02}) N(\mathbf{x}_{12})}_{\text{nonlinear term}} \right]$$

with the Balitsky prescription for the running coupling

$$\mathcal{K}(\mathbf{x}_{ij}) = \frac{N_c \alpha_s(\mathbf{x}_{01}^2)}{2\pi^2} \left[\frac{\mathbf{x}_{01}^2}{\mathbf{x}_{20}^2 \mathbf{x}_{21}^2} + \frac{1}{\mathbf{x}_{20}^2} \left(\frac{\alpha_s(\mathbf{x}_{20}^2)}{\alpha_s(\mathbf{x}_{21}^2)} - 1 \right) + \frac{1}{\mathbf{x}_{21}^2} \left(\frac{\alpha_s(\mathbf{x}_{21}^2)}{\alpha_s(\mathbf{x}_{20}^2)} - 1 \right) \right]$$

- Commonly used in LO data comparisons

Same initial conditions used for both BFKL and BK to study effects of **evolution**

- Protons: MV^e model

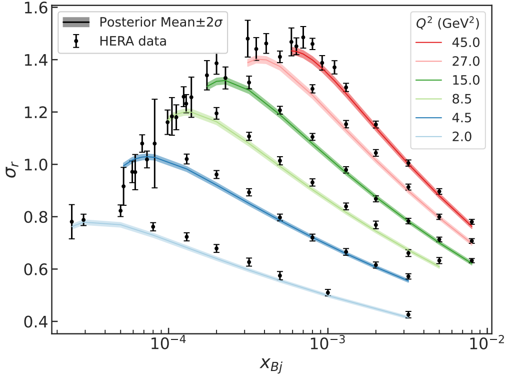
$$N_p(r, x_0) = 1 - \exp\left[-\frac{r^2 Q_{s,0}^2}{4} \log\left(\frac{1}{r\Lambda_{\text{QCD}}} + e_c \cdot e \right) \right]$$

  - Parameters taken from a Bayesian fit
    Casuga, Karhunen, Mäntysaari, 2311.10491
  - Impact parameter dependence assumed to factorize: $\int \mathrm{d}^2\mathbf{b} \to \sigma_0/2$

- Heavy nuclei: modeled using optical Glauber

$$N_A(r, x_0) = 1 - \exp\left[-AT_A(\mathbf{b}) \frac{\sigma_0}{2} \frac{r^2 Q_{s,0}^2}{4} \log\left(\frac{1}{r\Lambda_{\text{QCD}}} + e_c \cdot e \right) \right]$$

where $T_A(\mathbf{b})$ is the nuclear thickness function



Casuga, Karhunen, Mäntysaari, 2311.10491

Quarkonium wave function

- Quarkonium wave function is nonperturbative – adds uncertainty to the theory
- Various different approaches:

  nonrelativistic QCD, basis light-front quantization...
- We use the Boosted Gaussian that has been found to work well phenomenologically:

  Kowalski, Motyka, Watt, hep-ph/0606272

$$\phi_\lambda(r, z) = \mathcal{N}_\lambda \exp\left(-\frac{m^2 \mathcal{R}^2}{8z(1-z)} - \frac{2z(1-z)r^2}{\mathcal{R}^2} + \frac{m^2 \mathcal{R}^2}{2} \right)$$

where $\mathcal{N}_\lambda$, $\mathcal{R}$ are parameters fixed by normalization and leptonic decay width

Integrating over the transverse momentum exchange t

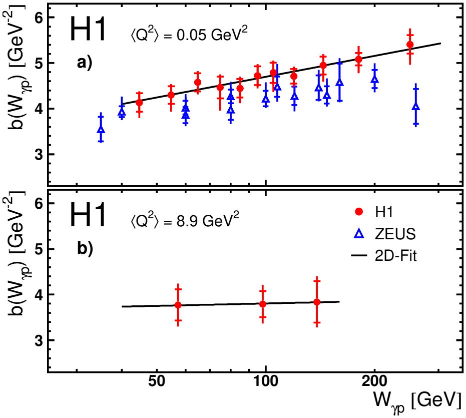
- Proton:
  - No impact parameter dependence in the model
  - Use the experimental parametrization:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t} = e^{-b|t|} \times \frac{\mathrm{d}\sigma}{\mathrm{d}t}(t=0)$$

  - b taken from a fit to experimental data

$$b = b_0 + 4\alpha' \log(W/W_0)$$

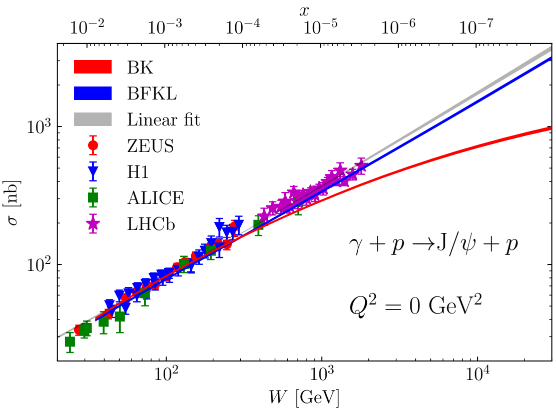
  - Modifies the energy dependence of the cross section
- Nucleus:
  - Impact parameter dependence taken into account:
    Can be integrated directly



H1 collaboration, hep-ex/0510016

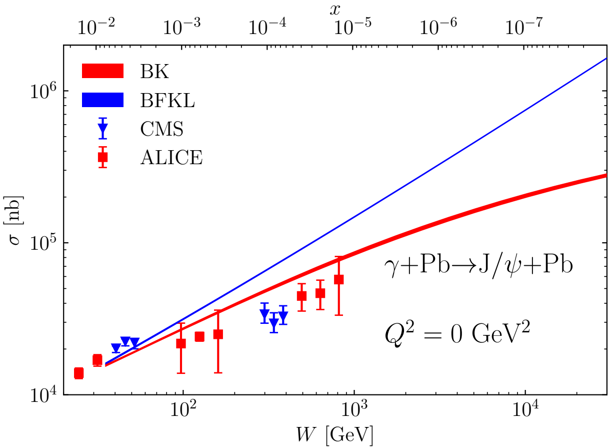
J/ψ production on protons

- The asymptotic slope ω_s in BFKL chosen such that it is close to "linear fit"
- Saturation effects too large at $W \gtrsim 1000\,\text{GeV}$
- Dipole amplitude not constrained by the HERA data in the region $x \lesssim 10^{-4}$
  - Effect of neglecting impact parameter **b** in the initial condition? (compare to JIMWLK approach Mäntysaari, Salazar, Schenke, 2207.03712)
- Saturation effects might be overestimated in this model

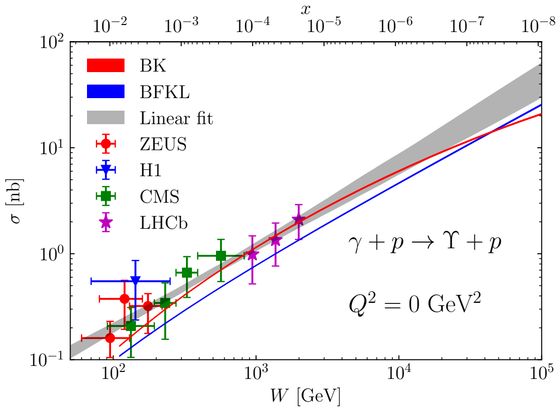


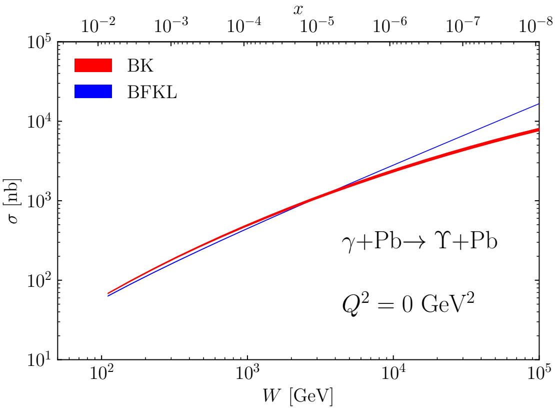
J/ψ production on nuclei

- Overall normalization of the results too large
- Deviation from BFKL prediction
- Saturation effects more important in Pb as expected
  - Factor of 2 difference at $W = 1000\,\text{GeV}$
- Impact-parameter dependence of the nuclear dipole amplitude more precise
- Note: In the domain $W \lesssim 1000\,\text{GeV}$ both BK and BFKL agree with proton data



Υ production

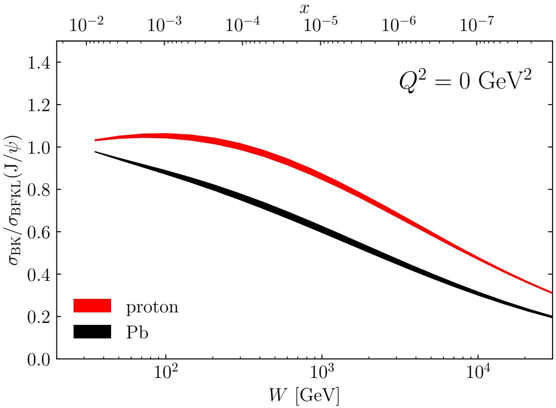


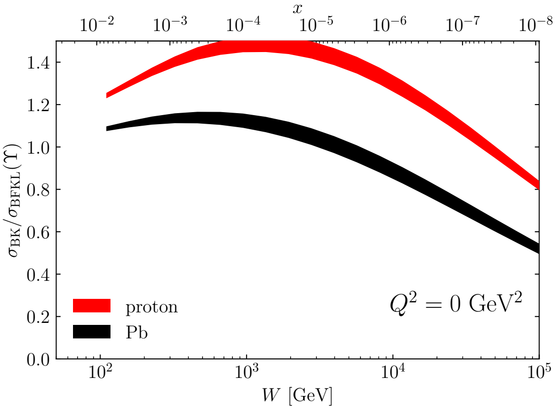


Smaller differences than in J/ψ production as expected:

Saturation effects are suppressed by $Q_s^2(x)/M_V^2$

Ratio $\sigma_{\mathrm{BK}}/\sigma_{\mathrm{BFKL}}$





- J/ψ: for nuclear targets falls before protons – saturation effects more important
- Υ: ratio mode flat, starts falling at higher energies

Nuclear suppression – impulse approximation

- Nuclear suppression usually studied with:

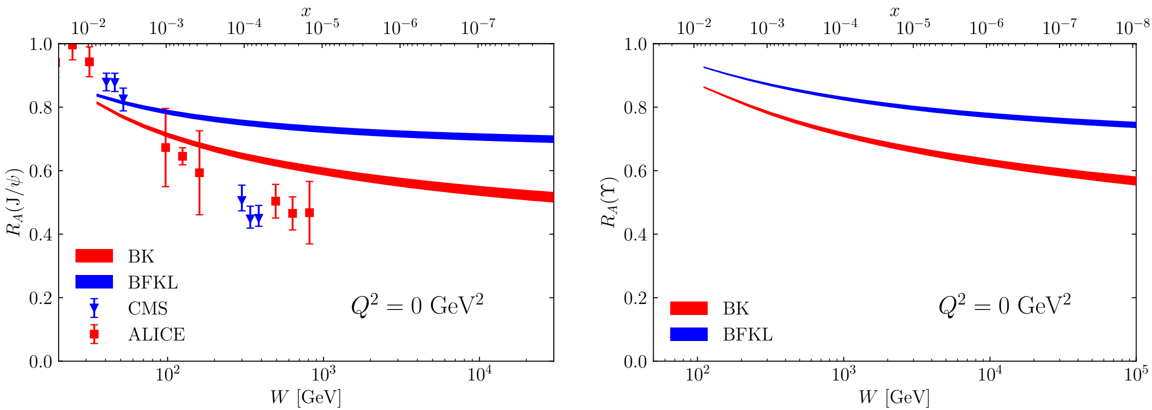
$$R_A = \sqrt{\sigma_A/\sigma_{\mathrm{IA}}}$$

where σ_{IA} is calculated using the impulse approximation:

$$\sigma_{\mathrm{IA}} = \frac{\mathrm{d}\sigma_p}{\mathrm{d}t}(t=0) \times 4\pi A^2 \int \mathrm{d}^2\mathbf{b}\, T_A(\mathbf{b})^2$$

- $R_A = 1$ in the linear region $rQ_s \ll 1$ for the initial condition

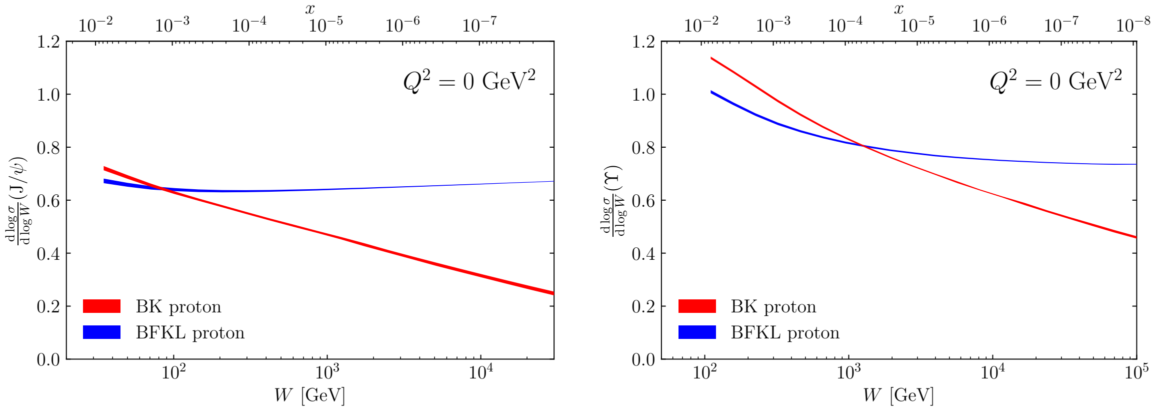
Nuclear suppression – results



Data seems to favor BK results – same effect as in σ_A plot

Note that R_A is not identically 1 for BFKL: effect of the initial condition used

Slope of the energy dependence: $\frac{\mathrm{d}}{\mathrm{d}\log W}\log\sigma$



Differences at lower values in W than for σ; however, more difficult to measure

High-energy behavior between BK and BFKL very different!

Summary

- We have compared results between nonsaturation (BFKL) and saturation (BK) approaches in exclusive quarkonium production
- Direct comparisons quite difficult – lots of different sources of theory uncertainty
- Saturation effects stronger for J/ψ than Υ as expected
- Saturation effects starting to be visible for heavy nuclei in LHC energies of J/ψ production
- The slope of energy dependence is especially sensitive to saturation
  - Generic BFKL prediction: linear as a function of W
  - Deviations of linear behavior $\Rightarrow$ evidence of saturation

Backup

BFKL scheme

- Solve the BFKL in Mellin space:

$$N(r,x) = \int_{c-i\infty}^{c+i\infty} \frac{\mathrm{d}\gamma}{2\pi i} \left(\frac{x_0}{x}\right)^{\omega(\gamma)} r^{2\gamma} \tilde{N}(\gamma, x_0)$$

where

$$\tilde{N}(\gamma, x_0) = \int_0^\infty \mathrm{d}r^2 r^{2(-\gamma-1)} N(r, x_0)$$

is the Mellin transform of the initial condition

- The eigenvalue ω is given by solving $\omega = \frac{\alpha_s N_c}{\pi}\chi(\gamma,\omega)$ where

$$\chi(\gamma,\omega) = \frac{\omega\gamma_{GG}(\omega)}{2N_c}\left[\frac{1}{\gamma+\omega/2} + \frac{1}{1-\gamma+\omega/2}\right] + (1-\omega)\left[2\psi(1) - \psi(1+\gamma) - \psi(1+1-\gamma)\right]$$

and γ_{GG} is the DGLAP anomalous dimension

Khoze et al., hep-ph/0406135

Theory uncertainties

- Quark mass: $\sigma \sim 1/m^5$. Huge impact on the overall normalization!
- Wave function: Affects the relevant dipole sizes
- Phenomenological corrections:
  - Real part and skewness corrections
  - Only real part corrections implemented here for simplicity
  - Mostly changes the normalization. Slightly modifies energy dependence
- NLO: Some modification on the energy dependence
- Running-coupling prescription in the BK equation:
  - Some modification on the energy dependence
- Impact parameter dependence of protons neglected