# Exclusive vector meson production in the dipole picture

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# Exclusive vector meson production

$\gamma^* + A \to V + A$ where $V = \rho,\ \phi,\ \mathrm{J}/\psi,\ \Upsilon\ \ldots$

- This talk: focus on heavy mesons $\mathrm{J}/\psi$ and $\Upsilon$
- Ryskin, Z.Phys.C 57 (1993) 89-92:

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

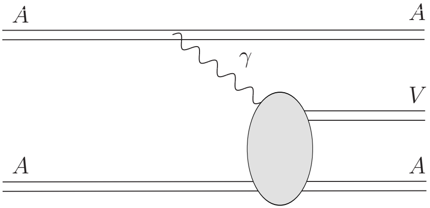
$\Rightarrow$ Very sensitive to the gluon structure of the target!

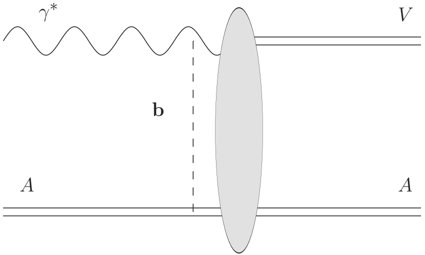
- Exclusive process:

  The total momentum transfer $\boldsymbol{\Delta}$ can be measured

  - Conjugate of the impact parameter **b**

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



# Coherent and incoherent vector meson production

## Coherent production

$$\sigma_{\text{coherent}} \sim |\langle \mathcal{A} \rangle|^2$$

- Target stays intact
- Probes the average interaction

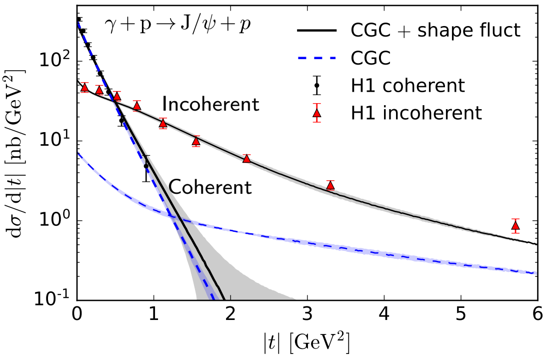
## Incoherent production

$$\sigma_{\text{incoherent}} \sim \langle |\mathcal{A}|^2 \rangle - |\langle \mathcal{A} \rangle|^2$$

- Target dissociates
- Probes Event-by-Event fluctuations

This talk: focus on coherent production

$\langle \ldots \rangle$ = average over target configurations




Mäntysaari, Salazar, Schenke, 2207.03712

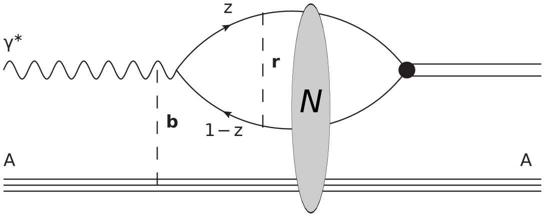
# Vector meson production at the leading order in the dipole picture

- Factorization in the high-energy limit:

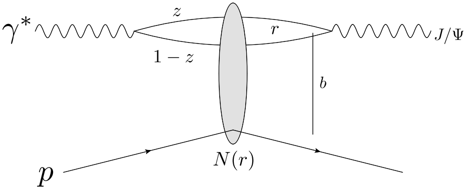
**Invariant amplitude for exclusive vector meson production**

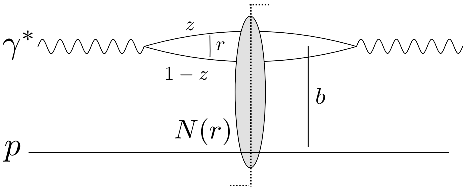
$$-i\mathcal{A}^{\lambda} = 2\int \mathrm{d}^2\mathbf{b}\,\mathrm{d}^2\mathbf{r}\,\frac{\mathrm{d}z}{4\pi}\,e^{-i\mathbf{b}\cdot\mathbf{\Delta}}\,\Psi_{\gamma^*}^{q\bar{q}}(\mathbf{r},z)\,N(\mathbf{r},\mathbf{b},Y)\,\Psi_{V}^{q\bar{q}*}(\mathbf{r},z), \qquad t = -\mathbf{\Delta}^2$$

- $\Psi_{\gamma^*}^{q\bar{q}}$: Photon light-front wave function
- $N$: Dipole-target scattering amplitude
- $\Psi_{V}^{q\bar{q}}$: Vector meson light-front wave function



# The dipole amplitude




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

Optical theorem:

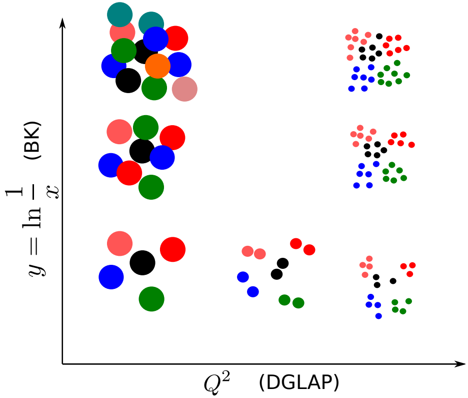
$\sigma^{\gamma^* p} \sim \text{dipole amplitude } N$

## Universal dipole amplitude

The same dipole amplitude $N = 1 - \frac{1}{N_c}\,\mathrm{Tr}\left[V(\mathbf{x})V^\dagger(\mathbf{y})\right]$ appears in different processes

- Inclusive DIS, exclusive VM production, single inclusive particle production in $p + A\ldots$
- Degrees of freedom at high energy: Wilson lines $V(\mathbf{x})$ and the dipole amplitude $N$

# Rapidity evolution of the dipole amplitude




Perturbative evolution equation in rapidity $Y = \ln \frac{1}{x}$

- JIMWLK equation

$\overset{\text{large } N_c}{\Longrightarrow}$ Balitsky-Kovchegov (BK) equation:

$$\frac{\partial}{\partial Y} N(\mathbf{x}_{01}) = \frac{N_c \alpha_s}{2\pi^2} \int \mathrm{d}^2 \mathbf{x}_2 \, \frac{\mathbf{x}_{01}^2}{\mathbf{x}_{20}^2 \mathbf{x}_{21}^2}$$

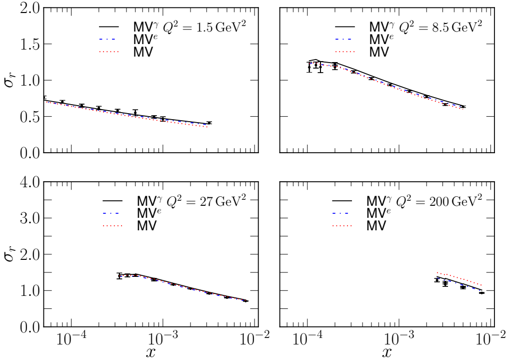
$$\times \left[ N(\mathbf{x}_{02}) + N(\mathbf{x}_{12}) - N(\mathbf{x}_{01}) - N(\mathbf{x}_{02}) N(\mathbf{x}_{12}) \right]$$

Needs a nonperturbative initial condition

Saturation at high energy (large $Y$):

Color Glass Condensate

# Initial condition for the dipole amplitude




Lappi, Mäntysaari, 1309.6963

- Common ansatz for the initial condition: the MV model and its generalizations

$$N_{\mathrm{MV}}(\mathbf{r}) = 1 - \exp\left[-\frac{1}{4}\mathbf{r}^2 Q_s^2 \ln\left(\frac{1}{\Lambda_{\mathrm{QCD}}^2 \mathbf{r}^2} + e\right)\right]$$

$Q_s$ = saturation scale

- The initial condition can be fitted to HERA $F_2$ data Albacete et al., 1012.4408
  - Gives a very good description of the data

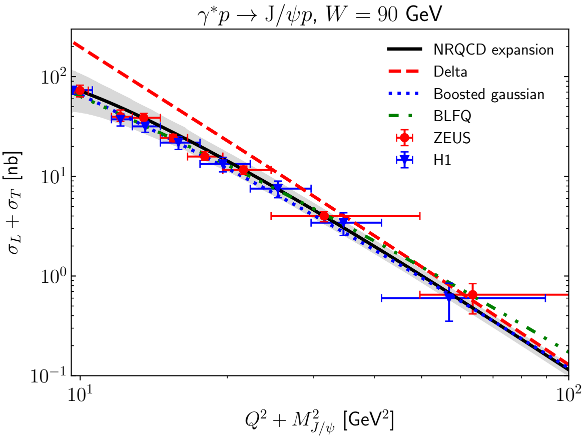
# Back to vector meson production: Vector meson wave function

## Invariant amplitude for exclusive vector meson production

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

- Now we have:
  - Photon wave function $\Psi_{\gamma^*}$ (perturbative, calculate using light-cone perturbation theory)
  - Dipole amplitude $N$ (nonperturbative initial condition + perturbative evolution)
- Final ingredient: vector meson light-front wave function
- The vector meson wave function is nonperturbative – a major source of uncertainty
- Heavy vector mesons: common assumption is the *nonrelativistic limit*
  - $q\bar{q}$ at rest $\Psi_V^{q\bar{q}}(\vec{k}) \sim \delta^{(3)}(\vec{k}) \Leftrightarrow \Psi_V^{q\bar{q}}(\mathbf{r},z) \sim \delta(z-\frac{1}{2})$

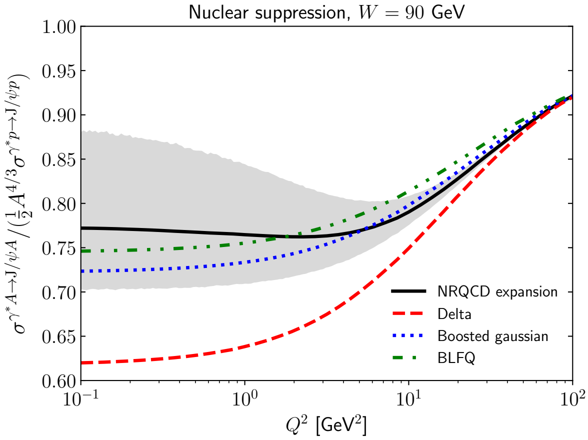
# $J/\psi$ production at LO as a function of the photon virtuality $Q^2$




Lappi, Mäntysaari, JP, 2006.02830

- *Delta* = nonrelativistic limit
- *NRQCD expansion* = include $v^2$ relativistic corrections using NRQCD matrix elements (developed in Lappi, Mäntysaari, JP, 2006.02830)
- *Boosted Gaussian, BLFQ* = phenomenological wave functions
- Nonrelativistic limit: disagreement with data at low $Q^2$
- Data described well by the other wave functions

# Nuclear suppression for $\mathrm{J}/\psi$ production at LO




Lappi, Mäntysaari, J.P, 2006.02830

- Quantified by the ratio

$$\frac{\sigma^{\gamma^* A \to \mathrm{J}/\psi A}}{\frac{1}{2} A^{4/3} \sigma^{\gamma^* p \to \mathrm{J}/\psi p}}$$

- Identically 1 without non-linear effects
- Wave function effects do not cancel at low $Q^2$

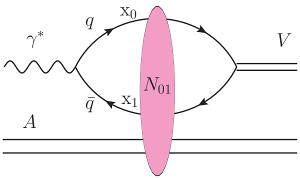
$\Rightarrow$ Important to use a realistic wave function when studying nuclear effects

# Exclusive vector meson production at NLO

## Invariant amplitude for exclusive vector meson production

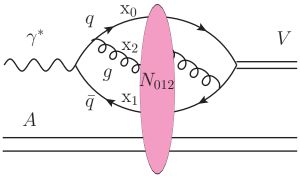
$$-iA_{t=0} = 2\int \mathrm{d}^2\mathbf{x}_0\,\mathrm{d}^2\mathbf{x}_1 \int \frac{\mathrm{d}z_0\,\mathrm{d}z_1}{(4\pi)}\delta(z_0+z_1-1)\Psi_{\gamma^*}^{q\bar{q}} N_{01} \Psi_{V}^{q\bar{q}*}$$

$$+2\int \mathrm{d}^2\mathbf{x}_0\,\mathrm{d}^2\mathbf{x}_1\,\mathrm{d}^2\mathbf{x}_2 \int \frac{\mathrm{d}z_0\,\mathrm{d}z_1\,\mathrm{d}z_2}{(4\pi)^2}\delta(z_0+z_1+z_2-1)\Psi_{\gamma^*}^{q\bar{q}g} N_{012} \Psi_{V}^{q\bar{q}g*}$$



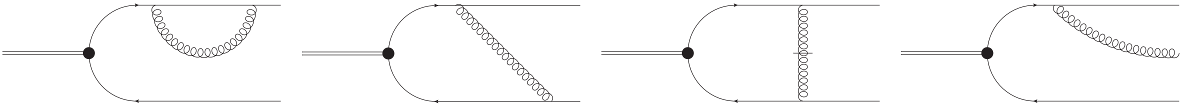

- Also contribution from the $q\bar{q}g$ state
- Need the wave functions for $q\bar{q}$ state at NLO
- Mean field limit: $N_{012} \approx \frac{N_c}{2C_F}\left[N_{02} + N_{12} - N_{02}N_{12} - \frac{1}{N_c^2}N_{01}\right]$
- Consider only $t = -\mathbf{\Delta}^2 = 0$ case:

  No need to model **b**-dependence of $N_{01}$



# Perturbative corrections to the wave functions

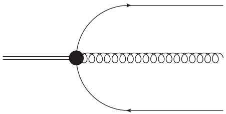
Meson wave function: nonperturbative part (leading-order wave function) + perturbative part



- In principle: also contribution from the nonperturbative part
- Heavy mesons: suppressed by the velocity $v$ of the quark $\Rightarrow \mathcal{O}(\alpha_s v^2)$

  $\Rightarrow$ Can be neglected at this order in perturbation theory

  Escobedo, Lappi, 1911.01136



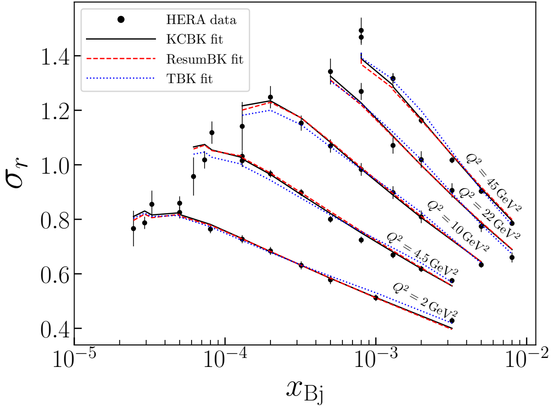
Photon wave function: Completely perturbative

Beuf, 1606.00777, 1708.06557; Hänninen, Lappi, Paatelainen, 1711.08207

Beuf, Lappi, Paatelainen, 2103.14549, 2112.03158, 2204.02486

# Initial condition fit for the dipole amplitude at NLO

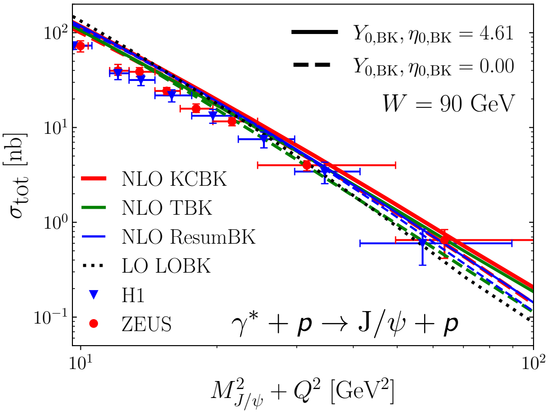
- Fit the initial condition of the dipole amplitude to the HERA structure function data
- NLO calculation: needs an NLO fit
- NLO BK: numerically heavy
  - Use different approximations: KCBK, ResumBK, TBK
  - Two starting points for the BK evolution: $Y_{0,\mathrm{BK}} = 0.00$ and $Y_{0,\mathrm{BK}} = 4.61$
- $3 \times 2 = 6$ different NLO dipole amplitude fits
- Note: only massless quarks in this fit



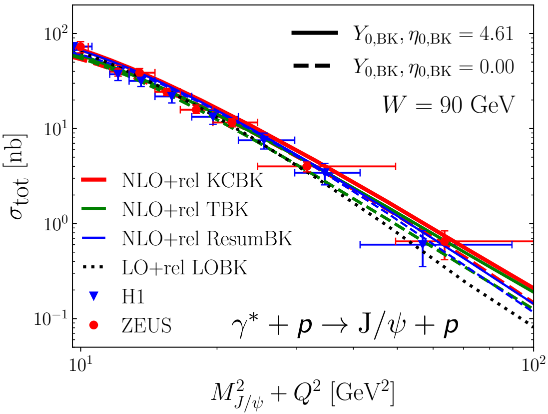

Beuf et al, 2007.01645

# Total $J/\psi$ production – dependence on the photon virtuality $Q^2$

Nonrelativistic limit



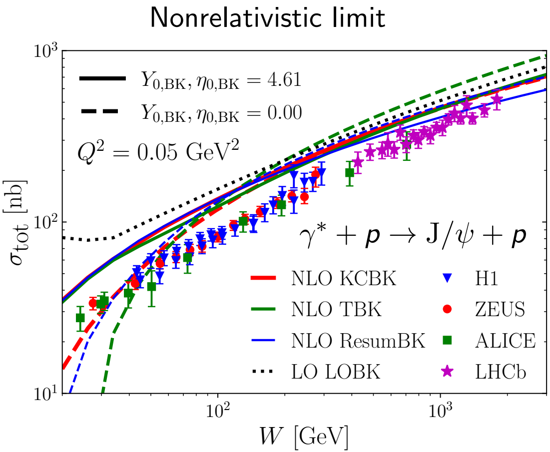

With $\alpha_s^0 v^2$ relativistic corrections

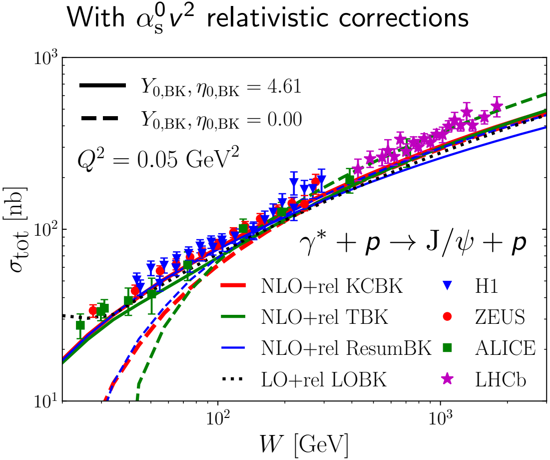



- NLO corrections moderate
- Good agreement with the data, $v^2$ corrections important at low $Q^2$

Mäntysaari, JP, 2204.14031

# Total $J/\psi$ production – dependence on the center-of-mass energy $W$




- $Y_{0,\mathrm{BK}} = 0.00$: unphysical results at low $W$

Mäntysaari, JP, 2204.14031

$\Rightarrow$ Additional constraints for the dipole amplitude fit from vector meson production

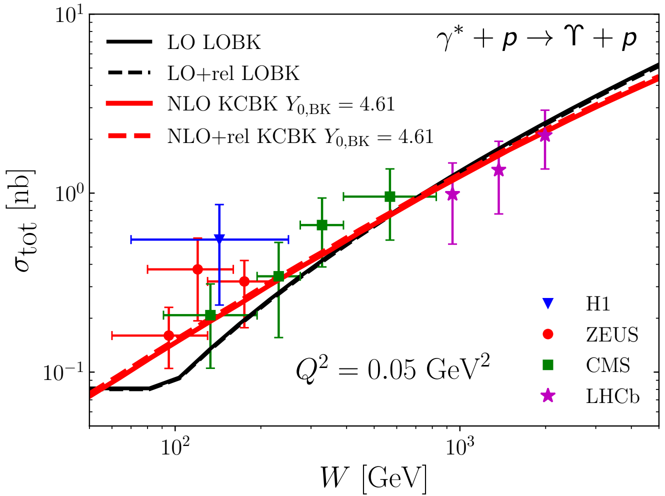
# Total $\Upsilon$ production – dependence on center-of-mass energy $W$

- $\Upsilon \approx b\bar{b}$:

  Relativistic effects expected to be smaller than for $J/\psi \approx c\bar{c}$

- $\alpha_s(M_\Upsilon)$ smaller $\Rightarrow$ better convergence of the power series

- Good agreement with the data




Mäntysaari, JP, 2204.14031

# Summary

- Exclusive vector meson production is highly sensitive to the target structure
- Some theoretical uncertainty coming from the meson wave function
    - For $\mathrm{J}/\psi$: Relativistic effects important at small $Q^2$
- NLO corrections moderate
    - NLO effects can be mostly captured by the LO dipole amplitude fit
- Future considerations
    - NLO with nuclear targets – more sensitive to saturation effects
- Important developments: precise measurements expected from ultra-peripheral collisions at the LHC and DIS measurements at the future Electron-Ion Collider