Higher-order corrections to exclusive heavy vector meson production

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Based on Phys. Rev. D 102, 054020 (2020) and [2104.02349]

15th of April, 2021

DIS 2021

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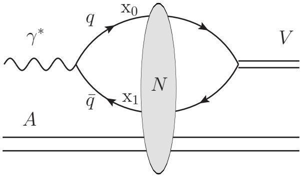
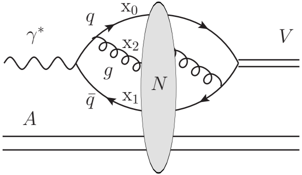
$$\frac{\mathrm{d}}{\mathrm{d}t}\sigma^{\gamma^*+A\to V+A}\bigg|_{t=0} = \frac{1}{16\pi}|\mathcal{A}|^2$$

$$-i\mathcal{A} = 2\int \mathrm{d}^2\mathbf{x}_0\,\mathrm{d}^2\mathbf{x}_1 \int \frac{\mathrm{d}z_0\,\mathrm{d}z_1}{(4\pi)}\delta(z_0+z_1-1)\Psi_{\gamma^*}^{q\bar{q}} N_{01} \Psi_V^{q\bar{q}*}$$
$$+ 2\int \mathrm{d}^2\mathbf{x}_0\,\mathrm{d}^2\mathbf{x}_1\,\mathrm{d}^2\mathbf{x}_2 \int \frac{\mathrm{d}z_0\,\mathrm{d}z_1\,\mathrm{d}z_2}{(4\pi)^2}\delta(z_0+z_1+z_2-1)\Psi_{\gamma^*}^{q\bar{q}g} N_{012} \Psi_V^{q\bar{q}g*} + \dots$$



- Mixed transverse coordinate, longitudinal momentum fraction space
- This process is sensitive to the gluon structure of the nucleus A
- Virtual photon light-front wave functions $\Psi_{\gamma^*}^{q\bar{q}}, \Psi_{\gamma^*}^{q\bar{q}g}$ from perturbative QCD [Beuf, Lappi and Paatelainen, 2103.14549]
- Energy dependence of the dipole-target amplitude N_{01} described by perturbative evolution equations, initial condition fitted to HERA data
- Meson light-front wave functions $\Psi_V^{q\bar{q}}, \Psi_V^{q\bar{q}g}$ nonperturbative

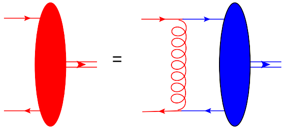


Higher-order corrections to the vector meson wave function

- Heavy vector meson Fock states: $|V\rangle = \Psi_V^{q\bar{q}} |q\bar{q}\rangle + \Psi_V^{q\bar{q}g} |q\bar{q}g\rangle + \text{higher orders}$
- Corrections in α_s and the heavy quark's velocity v
- Nonrelativistic expansion [Escobedo and Lappi, 1911.01136] (see Escobedo's talk on Tuesday):

$$\Psi_V^n = \sum_{m,k} C_{n\leftarrow m}^k \int_0^1 \frac{\mathrm{d}z'}{4\pi} \left(\frac{1}{m_q}\nabla\right)^k \phi^m(\mathrm{r}=0,z')$$

  - ϕ^m = leading-order wave function for Fock state m
  - α_s corrections in $C_{n\leftarrow m}^k$, relativistic corrections go as v^k



A loop correction to LFWF [1911.01136]

- We consider two types of higher-order corrections:

Relativistic corrections at LO, $\alpha_s^0 v^2$

$$\Psi_V^{q\bar{q}} = \sum_{k_1,k_2,k_3=0}^{2} \frac{1}{k_1!k_2!k_3!}(m_q r_1)^{k_1}(m_q r_2)^{k_2} 4\pi \left(-\frac{1}{2i}\partial_z\right)^{k_3} \delta(z-1/2) \times \int_0^1 \frac{\mathrm{d}z'}{4\pi} \frac{1}{m_q^{k_1+k_2}} [2i(z'-1/2)]^{k_3} \partial_1^{k_1} \partial_2^{k_2} \phi^{q\bar{q}}(\mathrm{r}=0,z')$$

NLO corrections in the nonrelativistic limit, $\alpha_s v^0$

$$\Psi_V^{q\bar{q}} = C_{q\bar{q}\leftarrow q\bar{q}}^0 \int_0^1 \frac{\mathrm{d}z'}{4\pi} \phi^{q\bar{q}}(\mathrm{r}=0,z')$$

$$\Psi_V^{q\bar{q}g} = C_{q\bar{q}g\leftarrow q\bar{q}}^0 \int_0^1 \frac{\mathrm{d}z'}{4\pi} \phi^{q\bar{q}}(\mathrm{r}=0,z')$$

Relativistic corrections

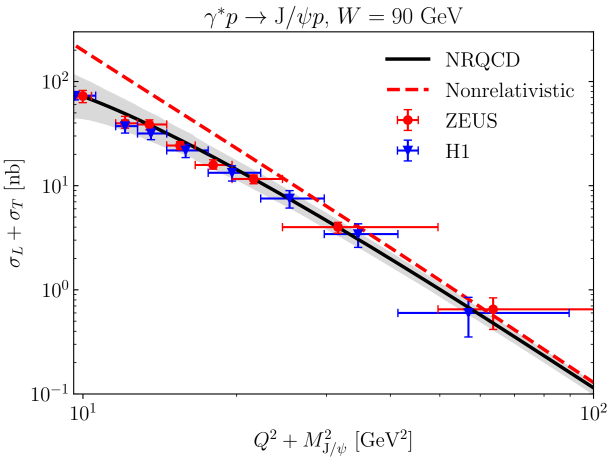
- Nonperturbative constants $\int_0^1 \frac{\mathrm{d}z'}{4\pi}[2i(z'-1/2)]^{k_3}\partial_1^{k_1}\partial_2^{k_2}\phi^{q\bar{q}}$
- Ansatz using the wave function in *rest frame* [Lappi, Mäntysaari, Penttala, 2006.02830]:

$$\phi(\vec{r}) = \phi(0) + \frac{1}{6}\nabla^2\phi(0)\vec{r}^2 + \mathcal{O}(v^4)$$

- Two unknown constants
  - Related to wave function and its derivative at origin $\vec{r} = 0$
  - For J/ψ: determined from charmonium decay widths using NRQCD (*Non-Relativistic QCD*) matrix elements [Bodwin et al., 0710.0994]
- From rest frame to light-front:
  - Different coordinate systems: (r_1, r_2, r_3) vs (r_1, r_2, z), $z =$ quark's fraction of the meson's plus-momentum
  - Different spinor bases: spin vs helicity (Melosh rotation = change of basis)
- See backup for the explicit form of the wave function

Relativistic corrections at LO in α_s: phenomenology

- *Nonrelativistic*: only the v^0 part
- *NRQCD*: v^2 corrections included
  - Error band from the uncertainty of the NRQCD matrix elements
- W = center-of-mass energy for the $\gamma^* p$ system
- Q^2 = photon virtuality
- Relativistic corrections are important at small Q^2
  - Large Q^2: v^2 corrections become almost negligible
- Including v^2 corrections results in a good agreement with the data



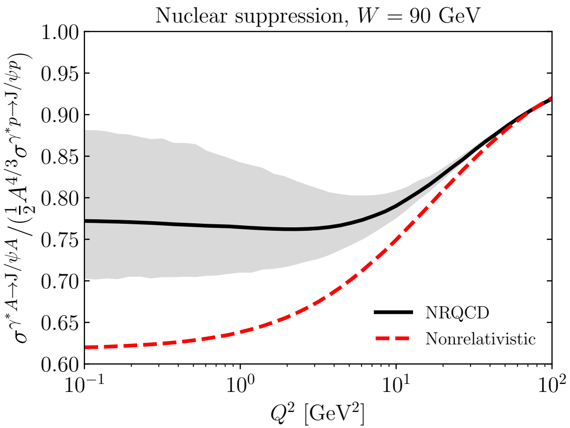
[Lappi, Mäntysaari, Penttala, 2006.02830]
HERA data from [hep-ex/0510016] and [hep-ex/0404008]

Relativistic corrections at LO in α_s: nuclear suppression in EIC kinematics

- We can study nuclear suppression with the quantity

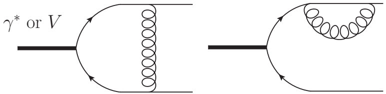
$$\frac{\sigma^{\gamma^* A \to \mathrm{J}/\psi A}}{\frac{1}{2} A^{4/3} \sigma^{\gamma^* p \to \mathrm{J}/\psi p}}$$

  - Heavy ion vs proton in the initial state
  - Identically 1 without non-linear effects
- Does the wave function cancel in this ratio?
  - At low Q^2 this does not happen!
  - Important to use a realistic wave function when comparing to EIC data

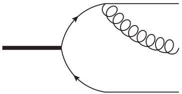


[Lappi, Mäntysaari, Penttala, 2006.02830]

$q\bar{q}$:



$q\bar{q}g$:



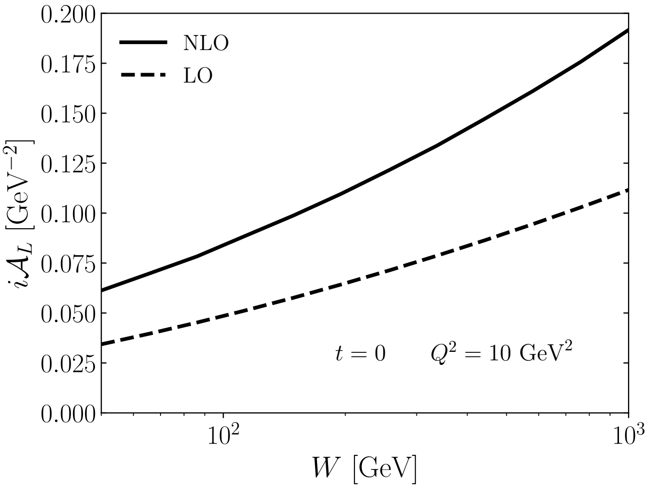
- We have calculated the production with longitudinal photon (transverse calculations on the way)
- UV divergences between the $q\bar{q}$ and $q\bar{q}g$ parts of the calculation cancel
- IR divergences cancel when one takes into account:
  - Renormalization of the leading-order wave function $\phi^{q\bar{q}}$
  - The energy dependence of the dipole amplitude which can be described in terms of the Balitsky-Kovchegov (BK) equation:

$$\frac{\partial}{\partial \ln(1/x)} N_{01} = \frac{N_c \alpha_s}{2\pi^2} \int \mathrm{d}^2 \mathrm{x}_2 \, \frac{\mathrm{x}_{01}^2}{\mathrm{x}_{20}^2 \mathrm{x}_{21}^2} \left[N_{02} + N_{12} - N_{01} - N_{02} N_{12} \right]$$

$\Rightarrow$ The total production amplitude is finite and can be numerically evaluated

NLO amplitude for $\gamma_L^* + p \to \mathrm{J}/\psi + p$

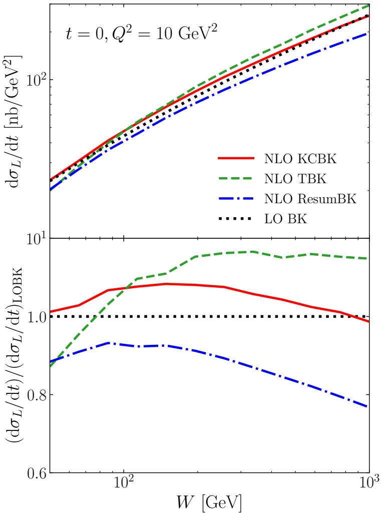
- We implemented the analytical expression for the production amplitude to numerical calculations
- NLO corrections are large
  - $\sim$ 75% of the LO result
- Significant increase of the amplitude



[Mäntysaari, Penttala, 2104.02349]

NLO cross section for $\gamma_L^* + p \to J/\psi + p$ with different dipole amplitudes

- …but comparing LO and NLO results is not that simple
- The dipole amplitudes need a fitted initial condition
  - Usually done using HERA structure function data
  - *BK* = LO fit [Lappi and Mäntysaari, 1309.6963]
  - *KCBK, TBK, ResumBK* = NLO fits [Beuf et al., 2007.01645]
    - See Hänninen's talk after this one
- The difference between the LO and NLO results is smaller than what the amplitude plot indicates
  - LO fit compensates for NLO effects
- Some variation between the different NLO fits
  - Complementary information to structure function analyses
  - Probe target structure at different length scales than structure functions



[Mäntysaari, Penttala, 2104.02349]

Summary

- Relativistic corrections to exclusive heavy vector meson production at order v^2 were determined
- NLO corrections to longitudinal production were calculated
- Relativistic corrections are important for small Q^2 while they become negligible at large Q^2
- NLO corrections found to be important in the calculation
  - However, LO dipole amplitude fit can capture most of the NLO effects
- Future work: NLO corrections to transverse production
  - Will allow comparison of the NLO results to the data
- Important developments: precise measurements expected at ultra-peripheral collisions at the LHC and the future Electron-Ion Collider

Backup

Backup - relativistic corrections to the wave function

$$\Psi_{+-}^{\lambda=0}(\mathrm{r},z) = \Psi_{-+}^{\lambda=0}(\mathrm{r},z) = \frac{\pi\sqrt{2}}{\sqrt{m_c}}\left[A\delta(z-1/2) + \frac{B}{m_c^2}\left(\left(\frac{5}{2}+\mathrm{r}^2 m_c^2\right)\delta(z-1/2) - \frac{1}{4}\partial_z^2\delta(z-1/2)\right)\right]$$

$$\Psi_{++}^{\lambda=1}(\mathrm{r},z) = \Psi_{--}^{\lambda=-1}(\mathrm{r},z) = \frac{2\pi}{\sqrt{m_c}}\left[A\delta(z-1/2) + \frac{B}{m_c^2}\left(\left(\frac{7}{2}+\mathrm{r}^2 m_c^2\right)\delta(z-1/2) - \frac{1}{4}\partial_z^2\delta(z-1/2)\right)\right]$$

$$\Psi_{+-}^{\lambda=1}(\mathrm{r},z) = -\Psi_{-+}^{\lambda=1}(\mathrm{r},z) = \left(\Psi_{-+}^{\lambda=-1}(\mathrm{r},z)\right)^* = \left(-\Psi_{+-}^{\lambda=-1}(\mathrm{r},z)\right)^* = -\frac{2\pi i}{m_c^{3/2}}B\delta(z-1/2)(r_1+ir_2)$$

$$\Psi_{--}^{\lambda=1}(\mathrm{r},z) = \Psi_{++}^{\lambda=-1}(\mathrm{r},z) = \Psi_{++}^{\lambda=0}(\mathrm{r},z) = \Psi_{--}^{\lambda=0}(\mathrm{r},z) = 0$$

$$A = \phi(0) = 0.213\ \mathrm{GeV}^{3/2}, \quad B = \frac{1}{6}\nabla^2\phi(0) = -0.0157\ \mathrm{GeV}^{7/2}$$

Fully nonrelativistic case:

$$A = 0.211\ \mathrm{GeV}^{3/2}, \quad B = 0$$