Exclusive heavy vector meson production at next-to-leading order in deep inelastic scattering

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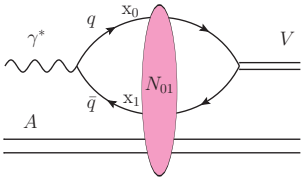
The dipole picture for exclusive vector meson production at NLO

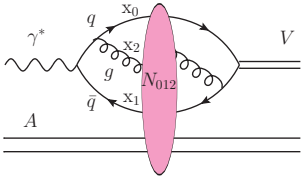
Invariant amplitude for exclusive vector meson production

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



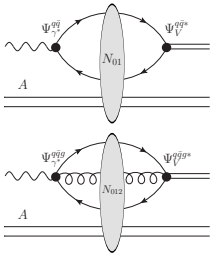
Three parts needed for the calculation:

- Virtual photon light-front wave functions $\Psi_{\gamma^*}^{q\bar{q}}, \Psi_{\gamma^*}^{q\bar{q}g}$ with massive quarks from perturbative QCD Beuf, Lappi, Paatelainen, 2103.14549, 2112.03158
- Dipole amplitude N whose energy dependence is described by perturbative evolution equations (e.g. BK)
- Meson light-front wave functions $\Psi_V^{q\bar{q}}, \Psi_V^{q\bar{q}g}$ nonperturbative
  - Use the nonrelativistic limit for the LO wave function $\phi^{q\bar{q}}(k) \sim \delta^3(k)$
  - NLO corrections perturbative Escobedo, Lappi, 1911.01136



Calculation of the NLO production amplitude

The NLO corrections bring up divergences that need to be treated properly



- 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 $\phi^{q\bar{q}}(\vec{r}=0)$
    - Can be related to the dimensionally regularized wave function

$$\int \frac{\mathrm{d}z'}{4\pi}\phi^{q\bar{q}} = \int \frac{\mathrm{d}z'}{4\pi}\phi^{q\bar{q}}_{\mathrm{DR}} \times \left[1 - \frac{\alpha_s C_F}{2\pi}\frac{1}{\alpha}\right]$$

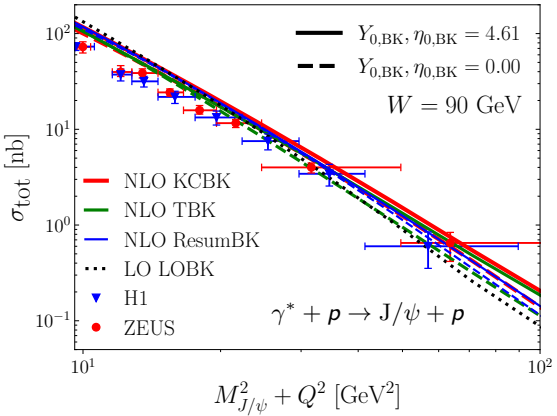
  - The rapidity dependence of the dipole amplitude which can be described in terms of the Balitsky-Kovchegov equation Balitsky, hep-ph/9509348; Kovchegov, hep-ph/9901281

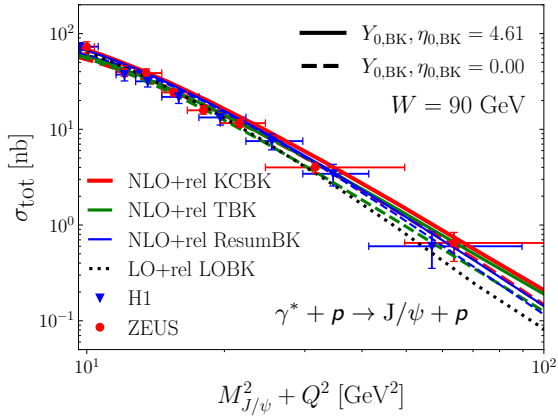
$\Rightarrow$ The total NLO production amplitude is finite and can be numerically evaluated

Longitudinal: Mäntysaari, J.P, 2104.02349 Transverse: Mäntysaari, J.P, In preparation

- Dipole amplitudes taken from Beuf et al. 2007.01645 (NLO) and Lappi, Mäntysaari, 1309.6963 (LO)
  - Initial condition fitted to HERA data
- We also include most important relativistic corrections of order v^2 at LO Lappi, Mäntysaari, J.P, 2006.02830

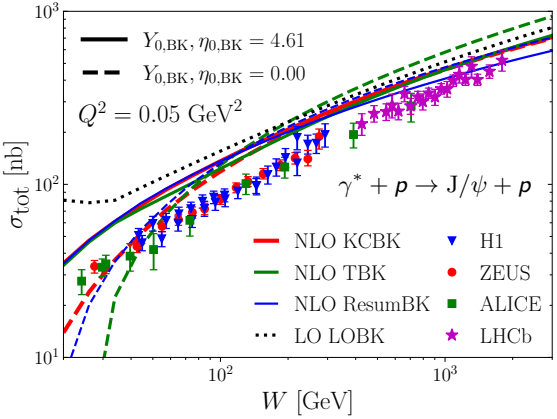
Total J/ψ production – dependence on the photon virtuality Q^2

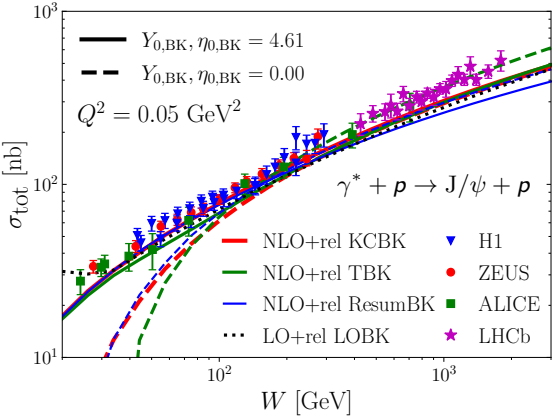




- NLO corrections moderate
- KCBK, TBK, ResumBK: BK with different resummations; $Y_{0,\mathrm{BK}}, \eta_{0,\mathrm{BK}}$: starting point for the BK evolution
- Including relativistic corrections improves agreement with the data at small Q^2

Total J/ψ production – dependence on the center-of-mass energy W





- Some differences in the W dependence between the different NLO dipole amplitude fits
- At small W, the $Y_{0,\mathrm{BK}} = 0.00$ dipoles behave unphysically
- Relativistic corrections important

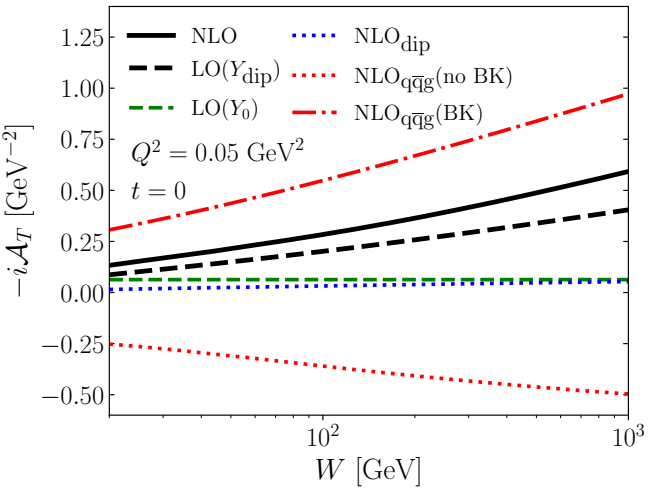
Summary

- We have calculated both longitudinal and transverse production of heavy vector mesons at NLO

  $\Rightarrow$ Comparisons with data possible
- NLO corrections are numerically important
  - However, the LO dipole amplitude fit can capture most of the NLO effects
- Generally good agreement with the data when v^2 relativistic corrections are included
- Can distinguish between different NLO dipole fits
  - At small W: Dipoles with $Y_{0,\mathrm{BK}} = 0.00$ give unphysical results
- Future:
  - Use NLO dipole fits with *massive* quarks – the dipole amplitudes in this work used a massless fit
  - t-dependence of heavy vector meson production
  - Light vector meson production at NLO at large Q^2 Mäntysaari, J.P, 2203.16911, see back-up
- Important developments: precise measurements expected at ultra-peripheral collisions at the LHC and the future Electron-Ion Collider

Backup – Decomposition of the production amplitude

- The leading order $\mathrm{LO}(Y_{\mathrm{dip}})$ result includes the resummation of the large logs $\sim \alpha_s \log 1/x$
- $\mathrm{NLO} = \mathrm{LO}(Y_0) + \mathrm{NLO}_{\mathrm{dip}} + \mathrm{NLO}_{\mathrm{q\bar{q}g}}$
- Significant increase of the amplitude
- Here the same dipole amplitude used for both LO and NLO
  $\Rightarrow \mathrm{NLO} - \mathrm{LO}(Y_{\mathrm{dip}})$ tells about the largeness of the NLO correction terms
  - Not the genuine difference between LO and NLO results:
    One has to use a dipole amplitude fitted at the corresponding order



Backup – Exclusive light vector meson production at NLO

- Calculated in Mäntysaari, J.P, 2203.16911, in the limit $Q^2 \gg M_V^2$
- Excellent agreement with the data