Exclusive meson production at NLO

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Motivation

Hard exclusive processes

- constrain generalized parton distributions
- t dependence $\rightsquigarrow$ distribution of partons in transverse plane correlated with momentum fraction x
- proton helicity flip distribution E $\rightsquigarrow$
  - orbital angular momentum
  - transverse polarization $\leftrightarrow$ spatial distribution of partons

Exclusive meson production (vs. DVCS)

- vector mesons $\rightsquigarrow$ enhanced sensitivity to gluons
- quantitative description more difficult

Factorization theorem

Collins, Frankfurt, Strikman '96

- light meson production $\gamma^* + p \to (\rho, \phi, \pi, \ldots) + p$
- limit of large Q^2
- valid from low to high x_B

collinear factorization: amplitude $\propto$ convolutions $\mathcal{F}(\xi, t, Q^2)$

$$\mathcal{F} = \sum_{a=q,g} \int dx\, F^a(x, \xi, t; \mu_F)\, K^a\Big(x, \xi, z, \log\frac{\mu_F^2}{Q^2}, \log\frac{\mu_R^2}{Q^2}\Big)\, \phi(z; \mu_F)$$

$\xi = x_B/(2 - x_B)$

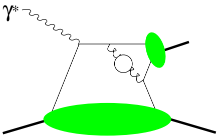
$F^a =$ generalized parton distribution $H^a, E^q, \tilde{H}^a, \tilde{E}^a$

$\phi =$ meson light-cone distribution amplitude

$K^a =$ hard scattering kernel: known to NLO

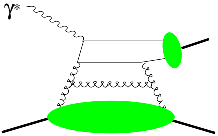
D. Ivanov, L. Szymanowski, G. Krasnikov '04

NLO graphs (vector mesons)

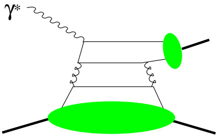


flavor singlet and nonsinglet

$u + d + s \qquad u - d,\ d - s$



gluons



flavor singlet

$\gamma_L^* p$ cross section

unpol. target

$$\sigma_L \propto (1-\xi^2)\,|\mathcal{H}|^2 - \Big(\xi^2 + \frac{t}{4M_p^2}\Big)\,|\mathcal{E}|^2 - 2\xi^2\,\mathrm{Re}\big(\mathcal{E}^*\mathcal{H}\big)$$

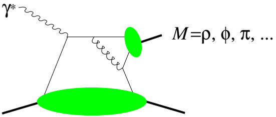
transverse target polarization

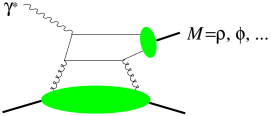
$$\sigma_L^{\uparrow} - \sigma_L^{\downarrow} \propto \frac{1}{M_p}\sqrt{t_0 - t}\,\sqrt{1-\xi^2}\;\mathrm{Im}\big(\mathcal{E}^*\mathcal{H}\big)$$

Warning

- factorization theorem valid for large Q^2
- at $Q^2 \sim$ few GeV^2 significant power corrections

  M. Vanderhaeghen et al. '98, S. Goloskokov and P. Kroll '05, '06
- in particular: parton k_T in hard propagators $\sim 1/(zQ^2 + k_T^2)$





- can take into account but then no NLO calculation
  same remark holds for color dipole models
- $\rightsquigarrow$ strategy: identify kinematics where NLO corr's moderate
  there may use LO calculation including power corrections

Results

Details of calculation (focus on H^g, H^q in this talk)

- double distribution model — Musatov, Radyushkin '99
- input distributions: CTEQ6M at $\mu_F = 1.3\,\mathrm{GeV}$
- LO evolution of GPDs — numerical code A. Vinnikov '06

- meson distribution amplitude: asymptotic form $\phi \propto z(1-z)$

- two-loop $\alpha_s(\mu_R)$ with $n_f = 3$

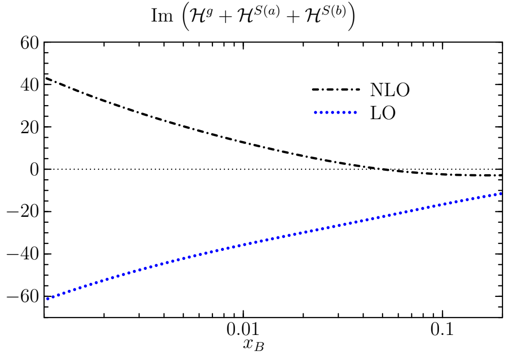
  $\alpha_s(m_c) = 0.395$

  $\alpha_s(m_Z) = 0.118$

Small x_B

numerically:

quark singlet + gluon, $\mu_F = \mu_R = Q = 4\,\mathrm{GeV}$

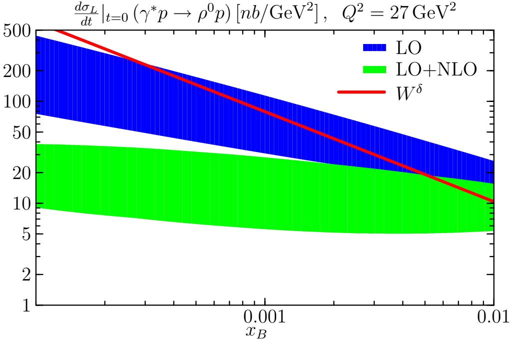


- large NLO term
- sign opposite to LO

Small x_B

numerically:

ρ cross section



- retain large scale uncertainty at NLO
- see no perturbative stability

W^δ with $\delta = 0.88$ (normalization arbitrary):
fit to prel. ZEUS data (EPS 2001) for $0.001 \lesssim x_B \lesssim 0.005$

analytically:

D. Ivanov et al. '04

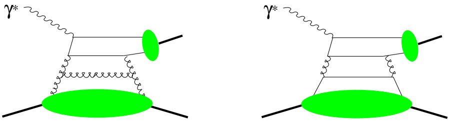
$$\xi \mathcal{H}^g \sim H^g(\xi,\xi,t) - \frac{3\alpha_s}{\pi}\left[\log\frac{\mu_F^2}{Q^2} + 2\right] \int_{1/2}^{1/(2\xi)} \frac{dy}{1+y}\, H^g\big((1+2y)\xi,\xi,t\big)$$

$$\mathcal{H}^q \sim H^q(\xi,\xi,t) - \frac{6\alpha_s}{\pi}\left[\log\frac{\mu_F^2}{Q^2} + 3\right] \int_{1/2}^{1/(2\xi)} dy\, H^q\big((1+2y)\xi,\xi,t\big)$$

for flavor singlet

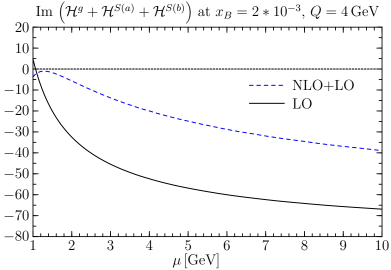
approx. numerically excellent for $\xi \lesssim 10^{-2}$

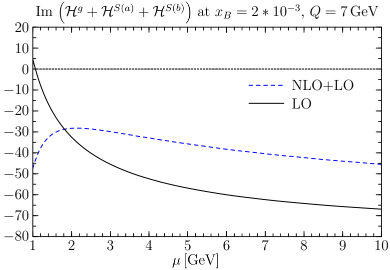
- with $H^g(x,\ldots) \sim$ flat and $H^q(x,\ldots) \sim 1/x$ * build up $\log 1/\xi$ terms = BFKL type logarithms



* remember that $H^g(x,0,0) = xg(x)$ and $H^q(x,0,0) = q(x)$

When do corrections become moderate?

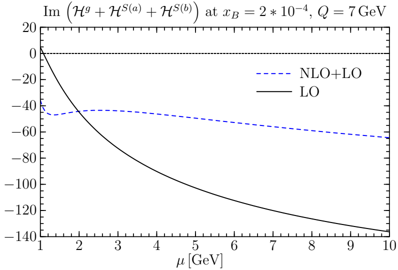




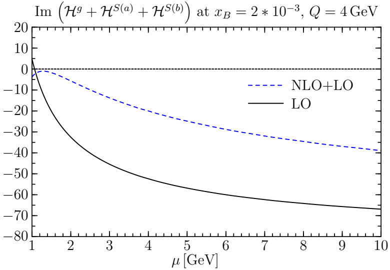
$x_B = 2 \times 10^{-3}$: corr's still large at $Q = 4\,\mathrm{GeV}$

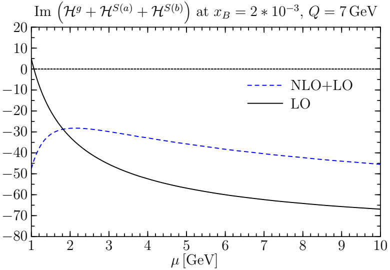
$x_B = 2 \times 10^{-4}$: no stability even at $Q = 7\,\mathrm{GeV}$

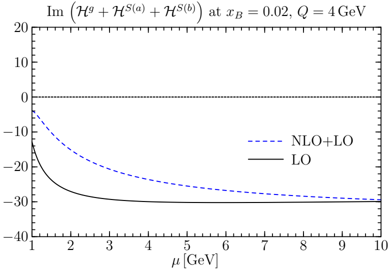
have set $\mu_F = \mu_R = \mu$



When do corrections become moderate?





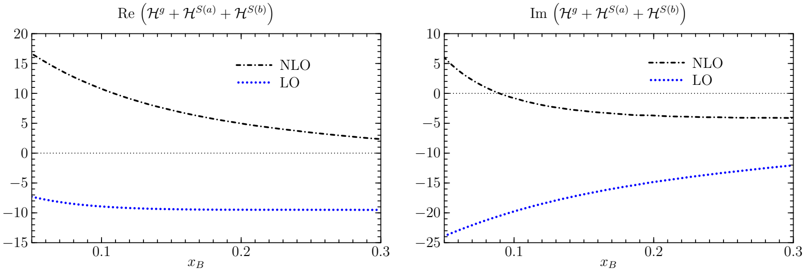


$x_B = 2 \times 10^{-2}$: corr's moderate at $Q = 4\,\mathrm{GeV}$

Fixed target kinematics

example $\mu_F = \mu_R = Q = 2\,\mathrm{GeV}$

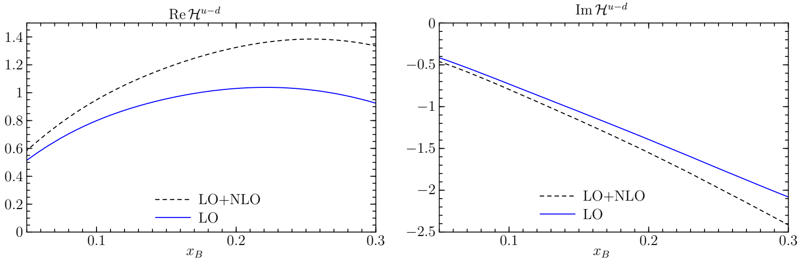
- gluons + quark singlet: corr's moderate for Im
- but still important for Re and smaller x_B
  no problem for $|\mathcal{H}|^2$ but possibly for $\mathrm{Im}\big(\mathcal{E}^*\mathcal{H}\big)$
  becomes better for $Q = 3\,\mathrm{GeV}$



Fixed target kinematics

example $\mu_F = \mu_R = Q = 2\,\mathrm{GeV}$

- quark flavor non-singlet: moderate corr's
  very similar for polarized quark terms $\widetilde{\mathcal{H}}$

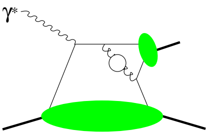


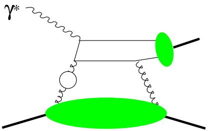
Choice of renormalization scale μ_R

- often discussed in literature: BLM scale setting
  choose μ_R so that β_0 terms vanish at NLO
- gluons: only term $\propto \beta_0 \log(\mu_R/\mu_F)$ $\rightsquigarrow$ $\mu_R = \mu_F$
  does not help with small-x logarithms
- quarks: structure of NLO corrections is

$$\text{large} - \beta_0 \Big[\text{large} - \text{small} \times \log \frac{Q^2}{\mu_R^2} \Big] - \text{tiny} \times \log \frac{Q^2}{\mu_F^2}$$

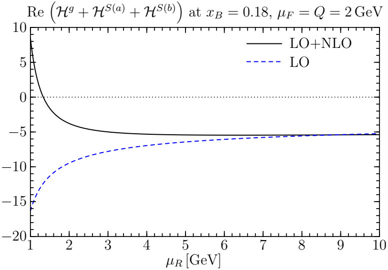
$\rightsquigarrow$ BLM requires $\mu_R \ll Q$ ... typically $\mu_R \lesssim 0.2\, Q$
only in perturbative region for very large Q^2
leaves large correction from β_0 independ't terms

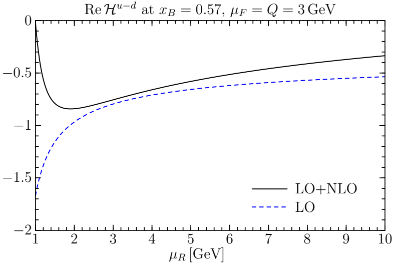




Choice of renormalization scale μ_R

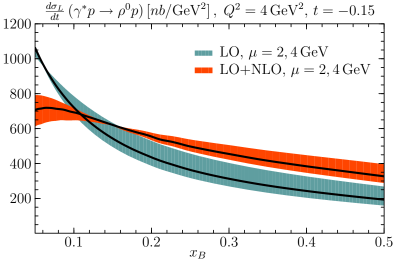
- for $\mu_R \lesssim 2\,\mathrm{GeV}$ typically find unstable behavior

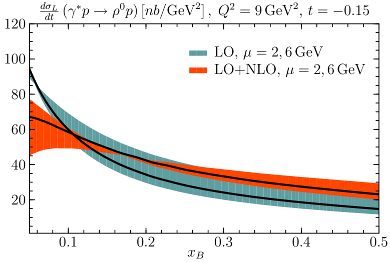




$\alpha_s(1.4\,\mathrm{GeV}) \approx 0.4$

Unpolarized cross section σ_L
in typical kinematics of Compass, HERMES, JLAB@12





central lines: $\mu_F = \mu_R = \mu = 3\,\mathrm{GeV}$ $\qquad$ $\mu_F = \mu_R = \mu = 4\,\mathrm{GeV}$

$\rightsquigarrow$ perturbative stability except if both x_B and Q^2 small

Polarized cross section $\sigma_L^{\uparrow} - \sigma_L^{\downarrow}$ in typical kinematics of Compass, HERMES, JLAB@12

$\boxed{\text{Work in progress}}$

Summary

in detailed numerical studies find

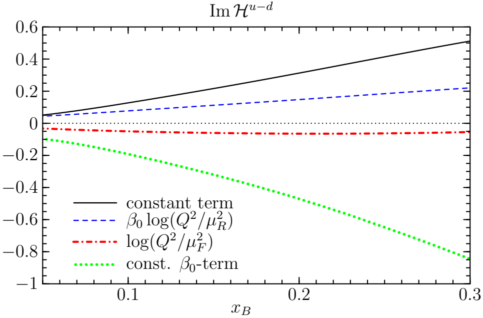
- small $x_B \lesssim 10^{-3}$: huge NLO corrections
  even for $Q^2 \sim$ several GeV^2
  $\rightsquigarrow$ must resum high-energy logarithms for reliable expressions
- moderate to large x_B :
  - gluon/singlet sector becomes gradually stable
  - quark non-singlet sector looks stable

  as long as Q not too small (want at least $Q^2 = 4\,\mathrm{GeV}^2$)
  scales μ_F and μ_R not chosen too small

Choice of scale

NLO correction for quarks:

$$\text{large} - \beta_0 \left[\text{large} - \text{small} \times \log \frac{Q^2}{\mu_R^2} \right] - \text{tiny} \times \log \frac{Q^2}{\mu_F^2}$$

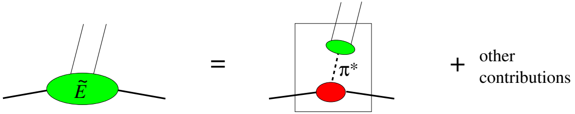


$$\mu_F = \mu_R = 2\,\mathrm{GeV}$$

Pseudoscalar mesons

see also: Belitsky and Müller '01

- quark GPDs most important
- convolutions with
  - $\tilde{H}^u - \tilde{H}^d$: similar to $H^u - H^d$
  - $\tilde{E}^u - \tilde{E}^d$: dominated by pion exchange



with asymptotic pion distribution amplitude:

$$\widetilde{\mathcal{E}} \propto 1 + \frac{\alpha_s}{\pi}\, 1.1 \times \left[3 + \log \frac{\mu_R^2}{Q^2}\right]$$

$\rightsquigarrow$ corrections moderate but not small

BLM scale $\mu_R^2 = e^{-14/3} Q^2 \approx 0.01 Q^2 \;\rightsquigarrow\; \widetilde{\mathcal{E}} \propto 1 - \frac{\alpha_s}{\pi}\, 1.8$