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NLO QCD Corrections to Exclusive Quarkonium Electroproduction

Zi Qiang Chen
University of Chinese Academy of Sciences

Based on arXiv: 1903.00171

In collaboration with Cong Feng Qiao

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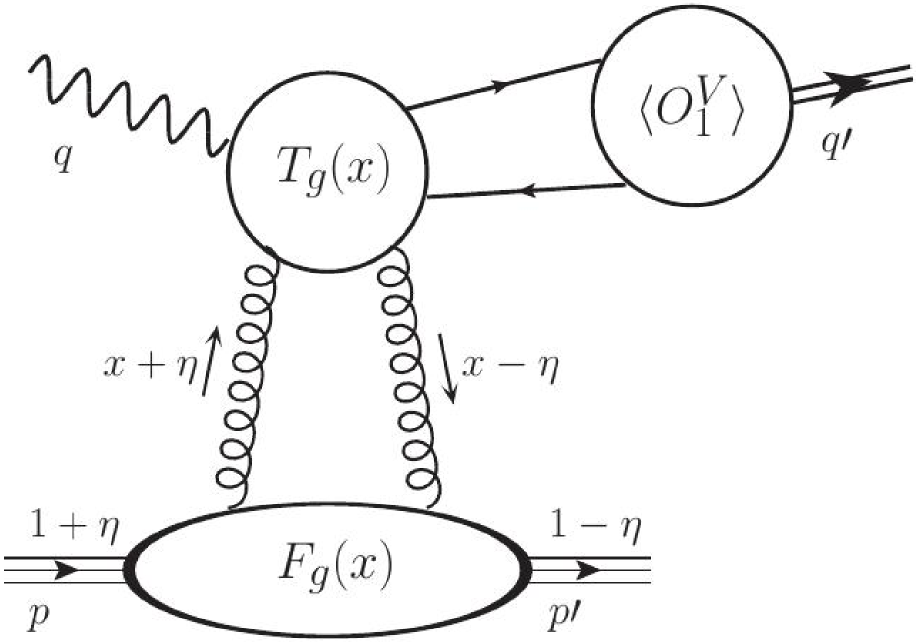
Introduction

We study the exclusive production of vector quarkonium:

$$\gamma^* p \to V p \; ,$$

with $V = J/\psi$ or Υ

real for photoproduction
virtual for electroproduction

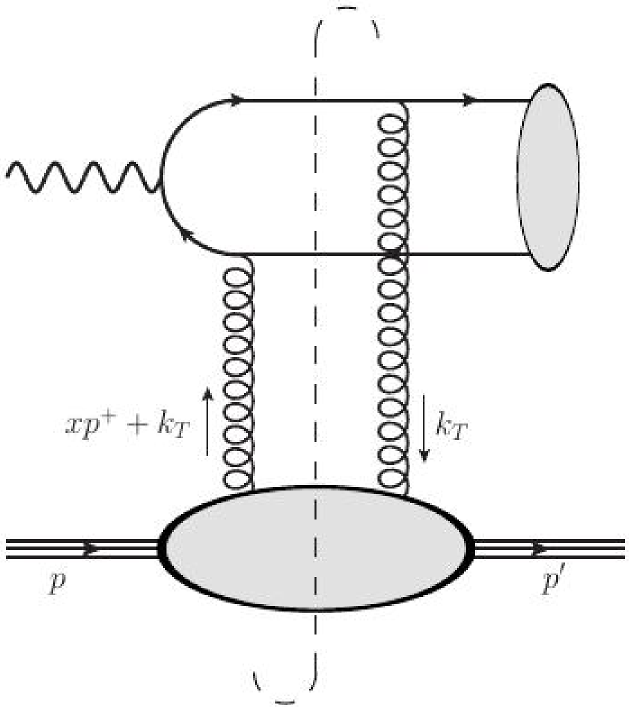


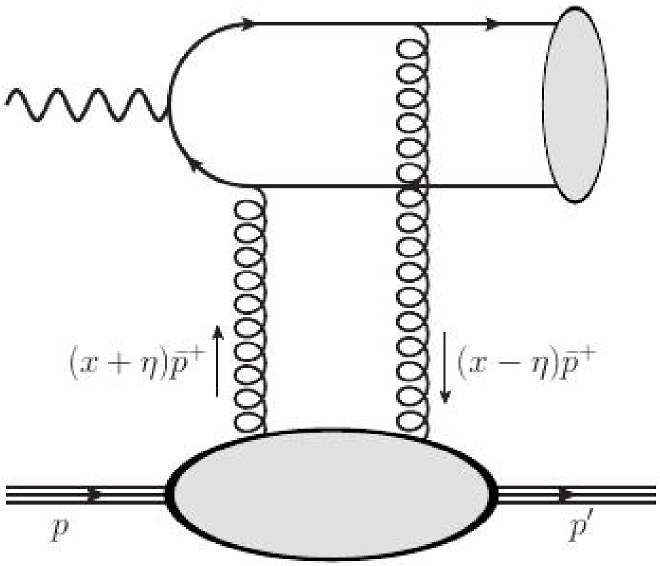
Introduction

Motivations:

- Study low x behaviour of the gluon distribution.
- Study pQCD validity in a large range of photon virtuality Q^2.
- Rich experimental data have been accumulated in HERA.
- For future, many projects are in progress or proposed, like ENC at FAIR, eRHIC at BNL, LHeC at CERN and EIC in China.

Introduction





k_T factorization:

- scaling limit: $s \to \infty,\ Q^2,\ m_V^2$ fixed
- Based on BFKL, resum $\log(1/x)$ term
- amplitude: $\mathcal{M} \propto \frac{\alpha_s(\bar{Q}^2)}{\bar{Q}^4} xg(x, \bar{Q}^2)$

QCD collinear factorization:

- scaling limit: $s \to \infty,\ m_V^2/s,\ Q^2/s$ fixed
- concept GPD (like the case of DVCS)
- amplitude: $\mathcal{M} \sim \int_{-1}^{1} C(x,\eta) F(x,\eta,t) dx$

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k_T factorization:

- The first step was made by Ryskin in 1993[1]. Some improvements were made in the following years[2].
- It is still unclear how to perform the full NLO calculation.

QCD collinear factorization:

- Going from LO to NLO is straightforward.
- NLO calculation for photoproduction were made by two groups[3,4].
- Perturbative convergence is poor for J/ψ photoproduction.
- We consider the more general electroproduction case, where the photon virtuality can provide an extra hard scale.

[1] M. G. Ryskin, Z. Phys. C 57, 89 (1993).
[2] A. D. Martin, C. Nockles, M. G. Ryskin, T. Teubner, Phys. Lett. B 662, 252 (2008).
[3] D. Yu. Ivanov, A. Schafer, L. Szymanowski, G. Krasnikov, Eur. Phys. J. C 34, 297 (2004); 75, 75(E) (2015).
[4] S. P. Jones, A. D. Martin, M. G. Ryskin, T. Teubner, J.Phys. G 43, 035002 (2016).

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Some technical details

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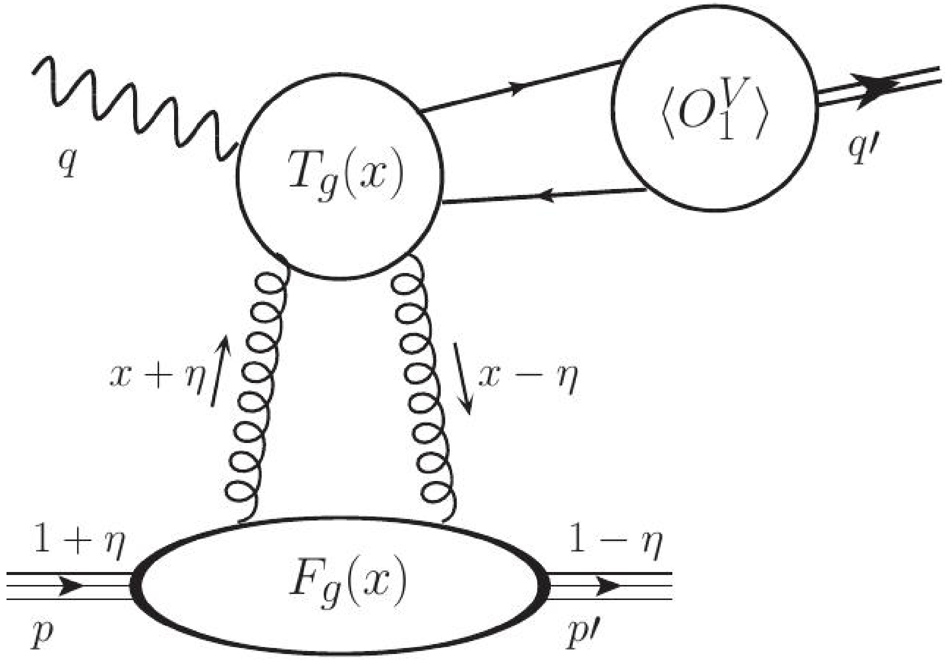
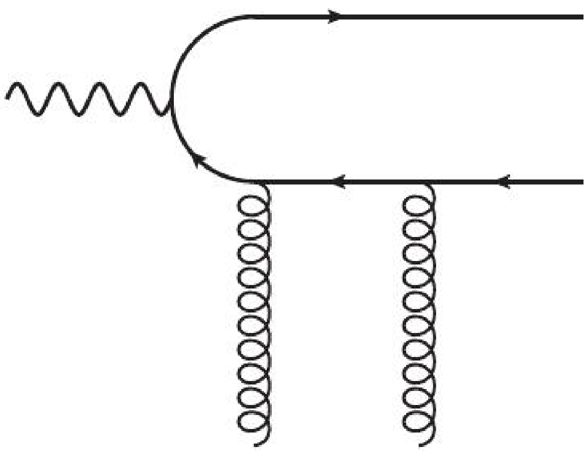
Factorization assumption :

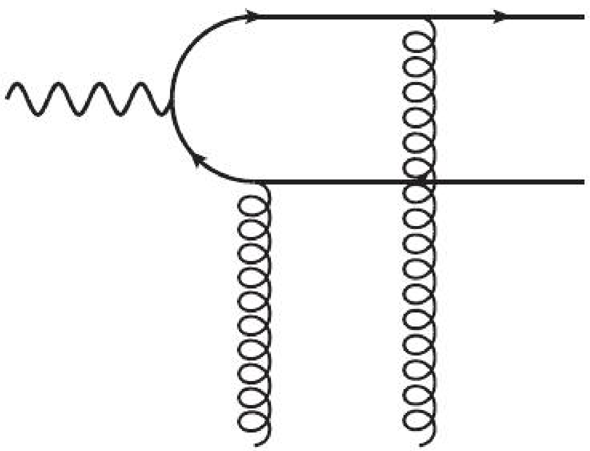
- Partonic process (hard scale $m_c^2,\ Q^2$)
  $\gamma^* g \to [c\bar{c}]g$
  $\gamma^* q \to [c\bar{c}]q$
- transition from heavy quark pair to quarkonium state. Described by NRQCD LDMEs.
- parton distribution within nucleon, the GPD here.



Some technical details

Typical Feynman diagram at LO:





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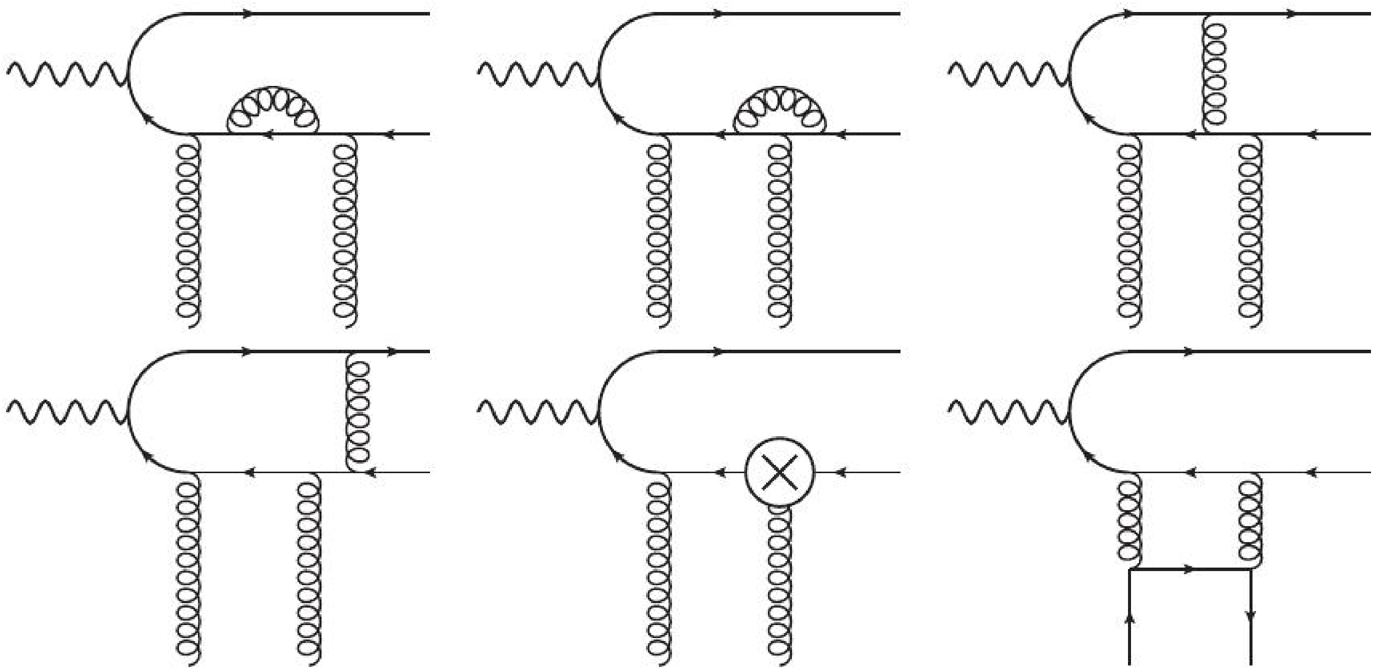
Typical Feynman diagram at NLO:



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Singularities:

- UV singularities: removed by renormalization.
- IR singularities: partly cancelled each other, the remaining absorbed into GPD:

$$F^p(x,\eta,\mu_F) = F^p(x,\eta) - \frac{1}{\epsilon}\left[\frac{\alpha_s}{2\pi}\frac{\Gamma(1-\epsilon)}{\Gamma(1-2\epsilon)}\left(\frac{4\pi\mu_R^2}{\mu_F^2}\right)^{\epsilon}\right]\sum_{p'}\int_{-1}^{1} V_{pp'}(x,y,\eta)F^{p'}(y,\eta)dy$$

We obtained finite analytical results for partonic amplitude. By taking limit $Q \to 0$, the amplitude of quarkonium photo-production can be reproduced.

Some technical details

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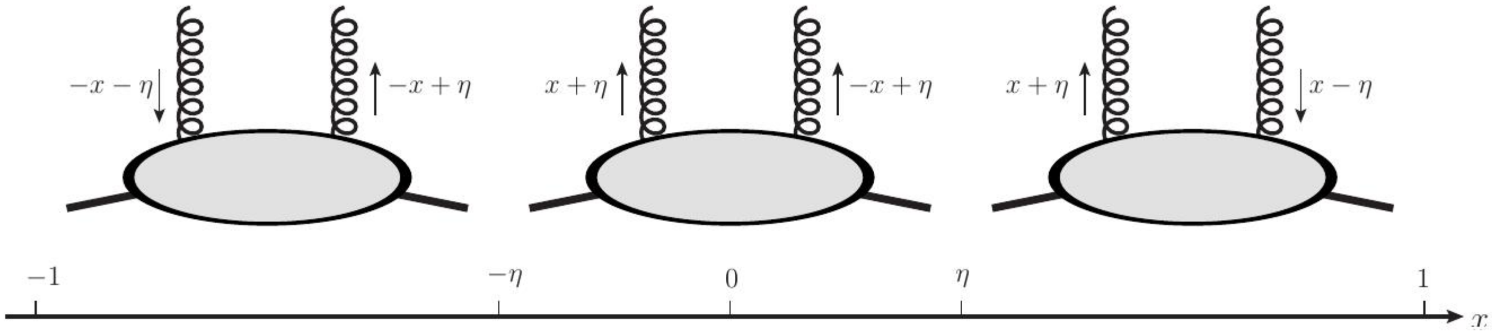
Full amplitude is the convolution of partonic amplitude with the GPD:

$$\mathcal{M} \sim \int_{-1}^{1} T^g(x,\eta) F_g(x,\eta) dx + \int_{-1}^{1} T^q(x,\eta) F_q(x,\eta) dx$$

- DGLAP region: $|x| > \eta$, ERBL region: $|x| < \eta$
- the imaginary parts of amplitude from DGLAP region



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Numerical analysis

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GPD model: initial condition + NLO GPD evolution equation

- Forward Model at $\mu_0 = 1\ \mathrm{GeV}$:

$$H^g(x,\eta,\mu_0) = xg(x,\mu_0),\ \ H^q(x,\eta,\mu_0) = q(x,\mu_0)\ \text{for}\ x > \eta$$

- GPD evolution equation:

$$\mu\frac{d}{d\mu}\boldsymbol{H}(x,\eta) = \int_{-1}^{1} dx'\boldsymbol{V}(x,x',\eta)\boldsymbol{H}(x',\eta)$$

The skewed effect at initial scale are neglected! But,

By compairing the GPD results from *Forward Model, Shuvaev-transformation approach, FMS Model, Double Distribution Model*, we find: as evolution proceeding, the discrepancy from initial condition shrunk.

Numerical analysis

For the real part of amplitude

- Unlike the case in DGLAP region, the properties of GPD at ERBL region are less clear.
- The imaginary parts of amplitude are dominant at high energy. In our case, $\mathrm{Re}\mathcal{M}/\mathrm{Im}\mathcal{M} < 0.5$.
- The real parts are restored via the derivative dispersion relation:

$$\mathrm{Re}\frac{\mathcal{M}}{s} \approx \tan\left(\frac{\pi}{2}\frac{d}{d\ln s}\right)\mathrm{Im}\frac{\mathcal{M}}{s} \approx \frac{\pi}{2}\frac{d}{d\ln s}\mathrm{Im}\frac{\mathcal{M}}{s}$$

the accuracy is about 1%.

Numerical analysis

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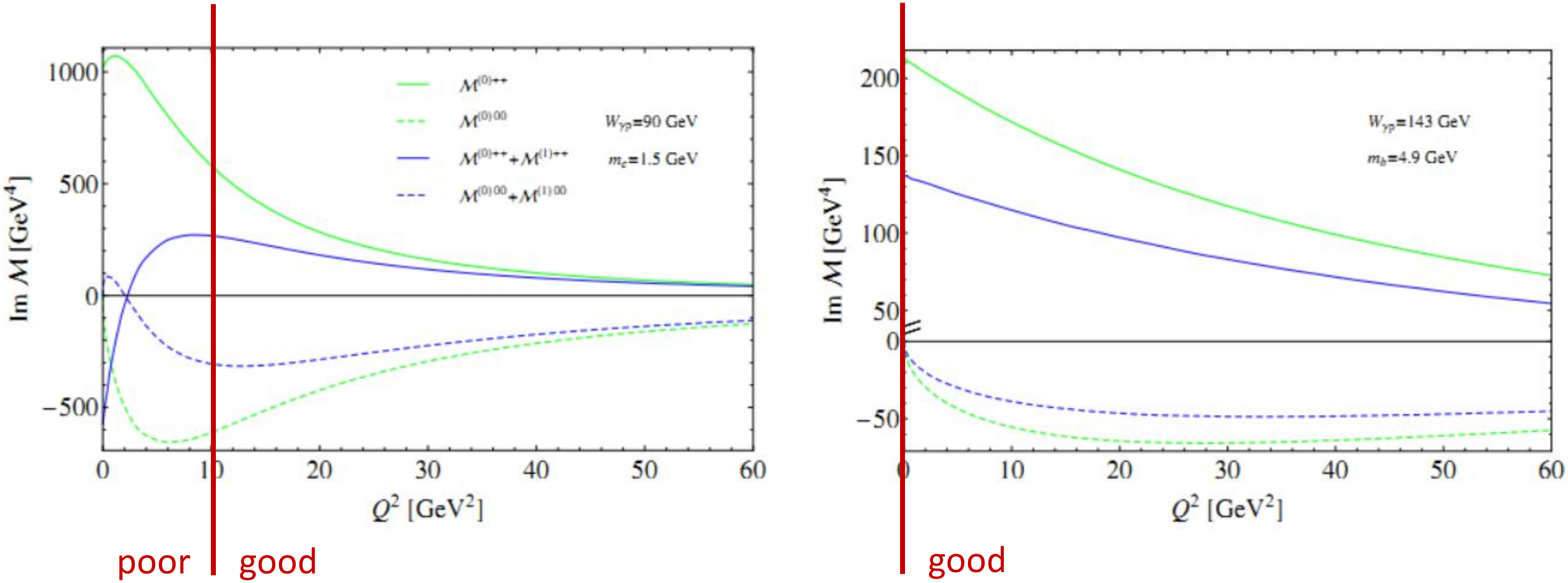
Exhibit perturbative convergence

$\mathrm{Im}\mathcal{M}$ as function of Q^2. Energy scale $\mu = \sqrt{m^2 + \frac{Q^2}{4}}$.

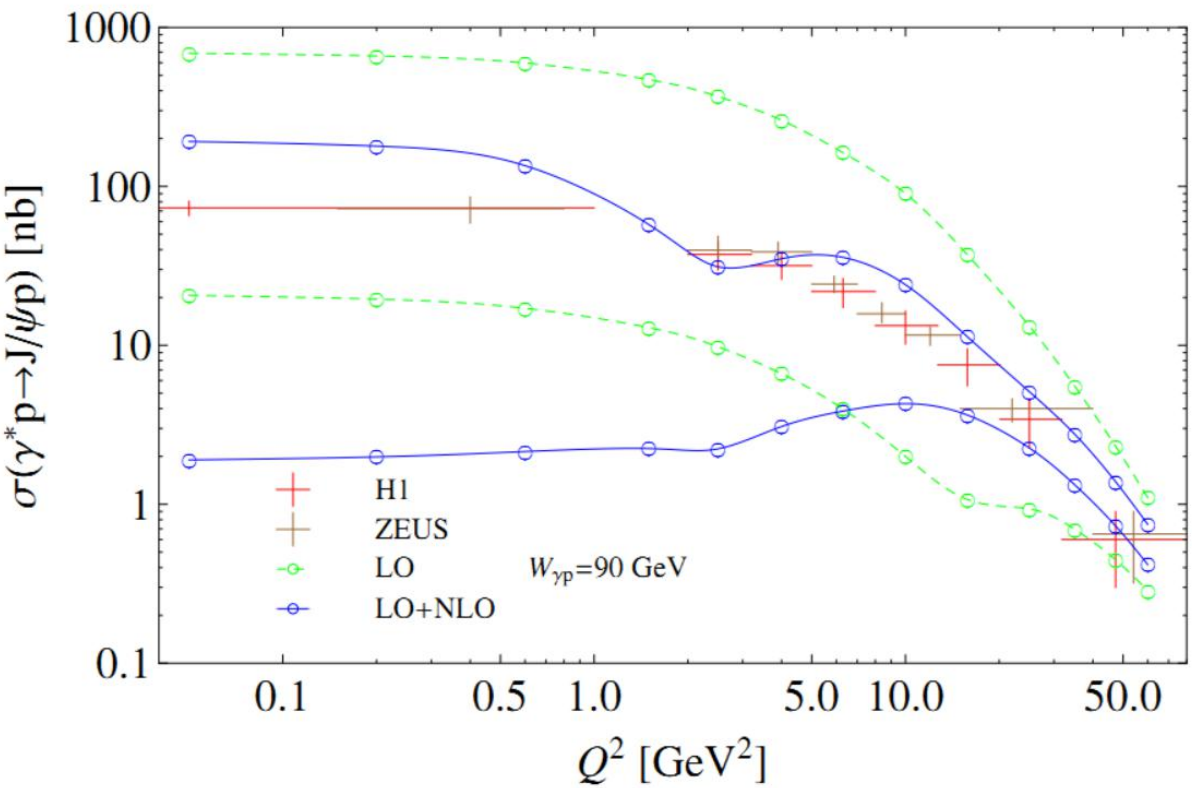


(a) J/ψ (b) Υ

Numerical analysis

J/ψ electroproduction at HERA

Cross section as function of Q^2.



Energy scale:

$$\left[\frac{1}{2}\sqrt{m^2+\frac{Q^2}{4}}\ ,\ 2\sqrt{m^2+\frac{Q^2}{4}}\right]$$

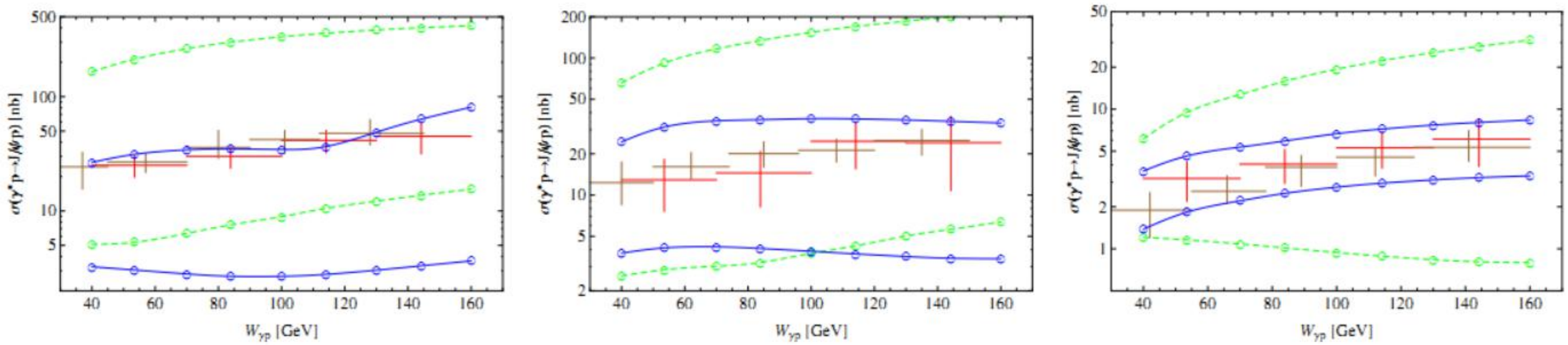
Quark mass:

$$[1.4\ ,\ 1.6]$$

Numerical analysis

J/ψ electroproduction at HERA

Cross section as function of W.



(a) $Q^2 = 3.2$ GeV (b) $Q^2 = 7.0$ GeV (c) $Q^2 = 22.4$ GeV

Numerical analysis

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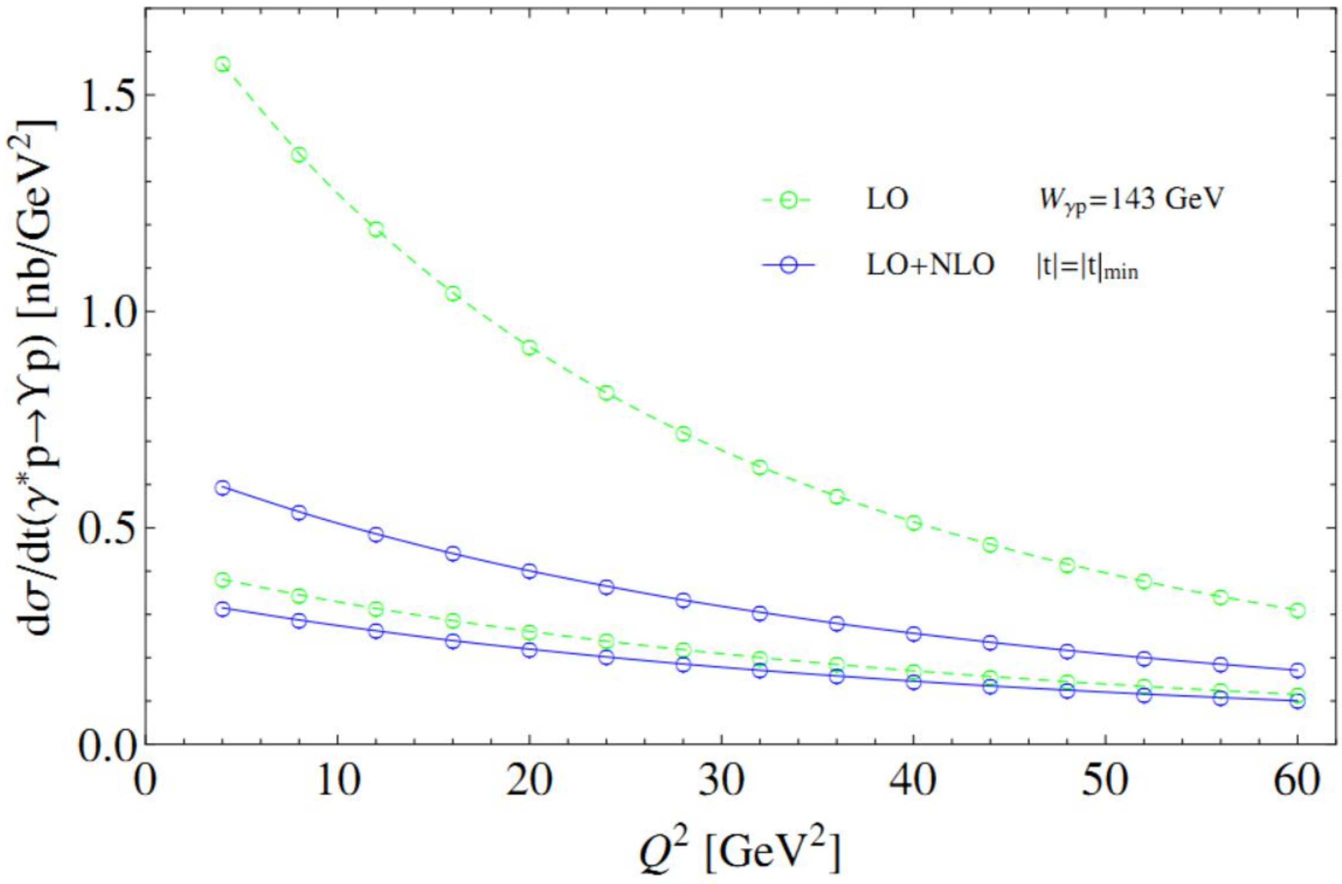
Prediction for ϒ electroproduction



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Summary

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- We calculated analytically the exclusive electroproduction of quarkonium in the NRQCD framework and collinear factorization scheme up to the NLO QCD accuracy.

- For J/ψ electroproduction, large photon virtuality is required to guarantee the legitimacy of pQCD use.

- At large Q^2, say $Q^2 > 10$ GeV^2, the NLO corrections may greatly reduce the theoretical uncertainty. We find a good agreement with the H1 and ZEUS data.

Summary

- At small η, the skewed effect of GPD mainly from the evolution. And the Forward Model is adequate to explain the data.

- In the future, we are expected to get more information on the GPD while confronting to the new experimental data.

Last...

THANKS