GPDs in high-mass photoproduction

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Prospects for extraction of GPDs from global fits of current and future data

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in collaboration with

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based on:

JHEP 1702 (2017) 054 [arXiv:1609.03830 [hep-ph]] ($\rho\gamma$ production)

JHEP 1811 (2018) 179 [arXiv:1809.08104 [hep-ph]] ($\pi\gamma$ production)

Motivation

1. The near forward photoproduction of a pair of particles with a large invariant mass is a case for a natural extension of collinear QCD factorization theorems which have been much studied for DVCS and for DVMP
2. It opens a new way to the extraction of GPDs, both chiral even and chiral odd, and to check their universality
3. Similar strategy was advocated by Strikman et al

S. Kumano, M. Strikman, and K. Sudoh, Phys. Rev. D80 (2009) 074003

A. B. Larionov and M. Strikman Phys. Lett. B760 (2016) 753

Collinear factorization
Twist 2 GPDs

Classification of twist 2 GPDs

- analogously, for gluons:
  - 4 gluonic GPDs without helicity flip:
    $H^g \xrightarrow{\xi=0,t=0}$ PDF $x\,g$
    E^g
    $\tilde{H}^g \xrightarrow{\xi=0,t=0}$ polarized PDF $x\,\Delta g$
    $\tilde{E}^g$
  - 4 gluonic GPDs with helicity flip:
    H_T^g
    E_T^g
    $\tilde{H}_T^g$
    $\tilde{E}_T^g$
    (no forward limit reducing to gluons PDFs here: a change of 2 units of helicity cannot be compensated by a spin 1/2 target)

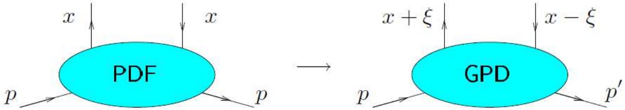
Chiral-odd sector: Transversity of the nucleon using hard processes

What is transversity?

- Transverse spin content of the proton:

$$\begin{array}{ccc} |\uparrow\rangle_{(x)} & \sim & |\rightarrow\rangle + |\leftarrow\rangle \\ |\downarrow\rangle_{(x)} & \sim & |\rightarrow\rangle - |\leftarrow\rangle \\ \text{spin along } x & & \text{helicity states} \end{array}$$

- Observables which are sensitive to helicity flip thus give access to transversity $\Delta_T q(x)$. Poorly known.
- Transversity GPDs are completely unknown experimentally.

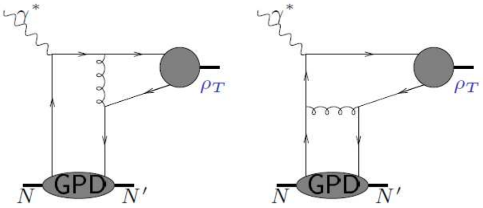


- For massless (anti)particles, chirality = (-)helicity
- Transversity is thus a chiral-odd quantity
- Since (in the massless limit) QCD and QED are chiral-even (γ^μ, $\gamma^\mu\gamma^5$), the chiral-odd quantities (1, γ^5, $[\gamma^\mu, \gamma^\nu]$) which one wants to measure should appear in pairs

Transversity of the nucleon using hard processes: using a two body final state process?

How to get access to transversity GPDs?

- the dominant DA of ρ_T is of twist 2 and chiral-odd ($[\gamma^\mu, \gamma^\nu]$ coupling)
- unfortunately $\gamma^* \, N^\uparrow \to \rho_T \, N' = 0$
    - This cancellation is true at any order : such a process would require a helicity transfer of 2 from a photon.
    - lowest order diagrammatic argument:



$$\gamma^\alpha [\gamma^\mu, \gamma^\nu] \gamma_\alpha \to 0$$

[Diehl, Gousset, Pire], [Collins, Diehl]

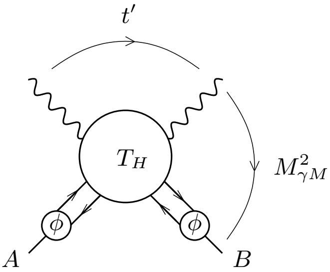
Transversity of the nucleon using hard processes: using a two body final state process?

Can one circumvent this vanishing?

- This vanishing only occurs at twist 2
- At twist 3 this process does not vanish [Ahmad, Goldstein, Liuti], [Goloskokov, Kroll]
- However processes involving twist 3 DAs may face problems with factorization (end-point singularities)
  can be made safe in the high-energy k_T-factorization approach
  [Anikin, Ivanov, Pire, LS, Wallon]
- One can also consider a 3-body final state process [Ivanov, Pire, LS, Teryaev], [Enberg, Pire, LS], [El Beiyad, Pire, Segond, LS, Wsllon]

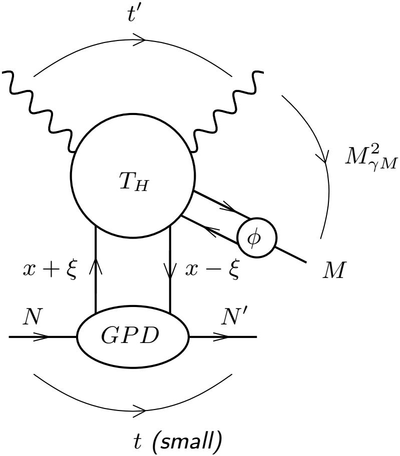
Probing GPDs using ρ or π meson + photon production

- We consider the process $\gamma\, N \to \gamma\, M\, N'$ $\quad M =$ meson
- Collinear factorization of the amplitude for $\gamma + N \to \gamma + M + N'$ at large $M^2_{\gamma M}$



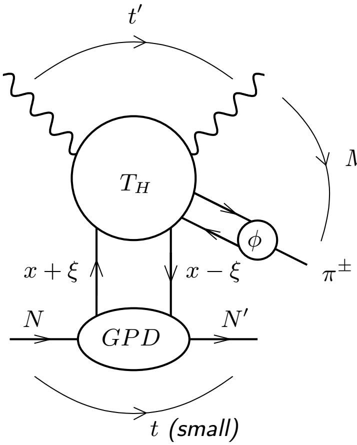
large angle factorization
à la Brodsky Lepage

$\longrightarrow$



Probing chiral-even GPDs using π meson + photon production

Processes with 3 body final states can give access to chiral-even GPDs

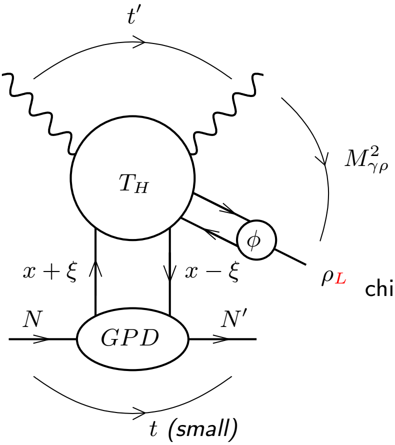


chiral-even twist 2 DA

chiral-even twist 2 GPD

Probing chiral-even GPDs using ρ meson + photon production

Processes with 3 body final states can give access to chiral-even GPDs

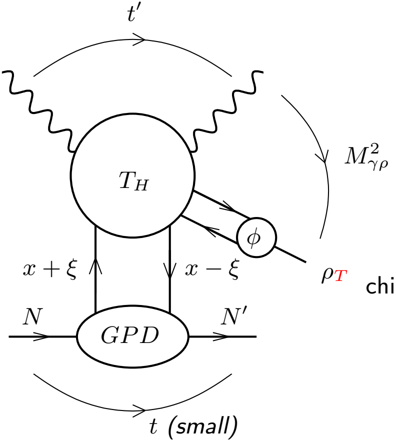


chiral-even twist 2 DA

chiral-even twist 2 GPD

Probing chiral-odd GPDs using ρ meson + photon production

Processes with 3 body final states can give access to chiral-odd GPDs



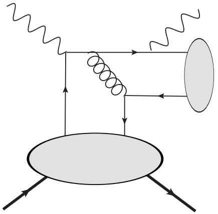
chiral-odd twist 2 DA

chiral-odd twist 2 GPD

Probing chiral-odd GPDs using ρ meson + photon production

Processes with 3 body final states can give access to chiral-odd GPDs

How did we manage to circumvent the no-go theorem for $2 \to 2$ processes?



Typical non-zero diagram for a transverse ρ meson

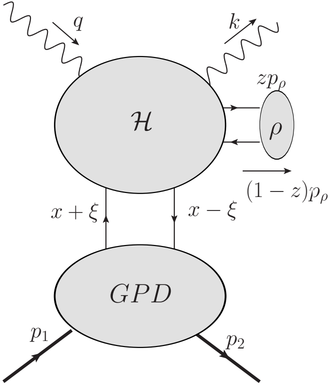
the σ matrices (from DA and GPD sides) do not kill it anymore!

Master formula based on leading twist 2 factorization

The ρ example

$$\mathcal{A} \propto \int_{-1}^{1} dx \int_{0}^{1} dz \, T(x,\xi,z) \times H(x,\xi,t) \Phi_\rho(z) + \cdots$$

- Both the DA and the GPD can be either chiral-even or chiral-odd.
- At twist 2 the longitudinal ρ DA is chiral-even and the transverse ρ DA is chiral-odd.
- Hence we will need both chiral-even and chiral-odd non-perturbative building blocks and hard parts.

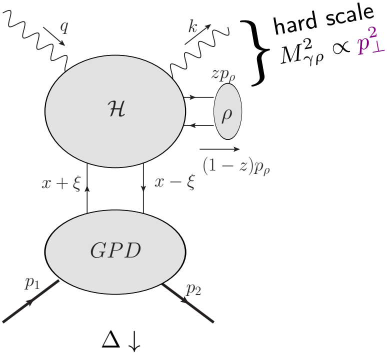


Kinematics

Kinematics to handle GPD in a 3-body final state process

- use a Sudakov basis :
  light-cone vectors p, n with $2\,p\cdot n = s$
- assume the following kinematics:
  - $\Delta_\perp \ll p_\perp$
  - $M^2,\ m_\rho^2 \ll M_{\gamma\rho}^2$
- initial state particle momenta:
  $q^\mu = n^\mu,\ p_1^\mu = (1+\xi)\,p^\mu + \frac{M^2}{s(1+\xi)} n^\mu$
- final state particle momenta:

$$
\begin{aligned}
p_2^\mu &= (1-\xi)\,p^\mu + \frac{M^2+\vec{p}_t^{\,2}}{s(1-\xi)} n^\mu + \Delta_\perp^\mu \\
k^\mu &= \alpha\, n^\mu + \frac{(\vec{p}_t-\vec{\Delta}_t/2)^2}{\alpha s} p^\mu + p_\perp^\mu - \frac{\Delta_\perp^\mu}{2}\,, \\
p_\rho^\mu &= \alpha_\rho\, n^\mu + \frac{(\vec{p}_t+\vec{\Delta}_t/2)^2+m_\rho^2}{\alpha_\rho s} p^\mu - p_\perp^\mu - \frac{\Delta_\perp^\mu}{2}\,,
\end{aligned}
$$



Non perturbative chiral-even building blocks

- Helicity conserving GPDs at twist 2 :

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p_2, \lambda_2 | \bar{\psi}_q \left(-\frac{1}{2}z^-\right) \gamma^+ \psi \left(\frac{1}{2}z^-\right) |p_1, \lambda_1\rangle$$

$$= \frac{1}{2P^+} \bar{u}(p_2, \lambda_2) \left[H^q(x,\xi,t)\gamma^+ + E^q(x,\xi,t) \frac{i\sigma^{\alpha+}\Delta_\alpha}{2m} \right]$$

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p_2, \lambda_2 | \bar{\psi}_q \left(-\frac{1}{2}z^-\right) \gamma^+\gamma^5 \psi \left(\frac{1}{2}z^-\right) |p_1, \lambda_1\rangle$$

$$= \frac{1}{2P^+} \bar{u}(p_2, \lambda_2) \left[\tilde{H}^q(x,\xi,t)\gamma^+\gamma^5 + \tilde{E}^q(x,\xi,t) \frac{\gamma^5\Delta^+}{2m} \right]$$

  - We will consider the simplest case when $\Delta_\perp = 0$.
  - In that case <u>and</u> in the forward limit $\xi \to 0$ only the H^q and $\tilde{H}^q$ terms survive.

- Helicity conserving (vector) DA at twist 2 :

$$\langle 0 | \bar{u}(0)\gamma^\mu u(x) | \rho^0(p,s)\rangle = \frac{p^\mu}{\sqrt{2}} f_\rho \int_0^1 du\, e^{-iup\cdot x} \phi_\parallel(u)$$

Non perturbative chiral-odd building blocks

- Helicity flip GPD at twist 2 :

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p_2, \lambda_2 | \bar{\psi}_q \left(-\frac{1}{2}z^-\right) i\sigma^{+i} \psi \left(\frac{1}{2}z^-\right) | p_1, \lambda_1 \rangle$$
$$= \frac{1}{2P^+} \bar{u}(p_2, \lambda_2) \left[H_T^q(x,\xi,t) i\sigma^{+i} + \tilde{H}_T^q(x,\xi,t) \frac{P^+\Delta^i - \Delta^+ P^i}{M_N^2} \right.$$
$$+ \left. E_T^q(x,\xi,t) \frac{\gamma^+\Delta^i - \Delta^+\gamma^i}{2M_N} + \tilde{E}_T^q(x,\xi,t) \frac{\gamma^+ P^i - P^+\gamma^i}{M_N} \right] u(p_1, \lambda_1)$$

  - We will consider the simplest case when $\Delta_\perp = 0$.
  - In that case and in the forward limit $\xi \to 0$ only the H_T^q term survives.

- Transverse ρ DA at twist 2 :

$$\langle 0 | \bar{u}(0) \sigma^{\mu\nu} u(x) | \rho^0(p,s) \rangle = \frac{i}{\sqrt{2}} (\epsilon_\rho^\mu p^\nu - \epsilon_\rho^\nu p^\mu) f_\rho^\perp \int_0^1 du\, e^{-iup\cdot x}\, \phi_\perp(u)$$

Models for DAs

Asymptotical DAs

- We take the simplistic asymptotic form of the (normalized) DAs (i.e. no evolution):

$$\phi_\pi(z) = \phi_{\rho_{||}}(z) = \phi_{\rho\perp}(z) = 6z(1-z)\,.$$

- For the π case, a non asymptotical wave function can be also investigated:

$$\phi_\pi(z) = \frac{8}{\pi}\sqrt{z(1-z)}\,.$$

(under investigation)

Model for GPDs: based on the Double Distribution ansatz

Realistic Parametrization of GPDs

- GPDs can be represented in terms of Double Distributions [Radyushkin] based on the Schwinger representation of a toy model for GPDs which has the structure of a triangle diagram in scalar ϕ^3 theory

$$H^q(x,\xi,t=0) = \int_{-1}^{1} d\beta \int_{-1+|\beta|}^{1-|\beta|} d\alpha\ \delta(\beta+\xi\alpha-x)\ f^q(\beta,\alpha)$$

- ansatz for these Double Distributions [Radyushkin]:
  - chiral-even sector:

$$\begin{aligned} f^q(\beta,\alpha,t=0) &= \Pi(\beta,\alpha)\, q(\beta)\Theta(\beta) - \Pi(-\beta,\alpha)\, \bar{q}(-\beta)\,\Theta(-\beta)\,, \\ \tilde{f}^q(\beta,\alpha,t=0) &= \Pi(\beta,\alpha)\, \Delta q(\beta)\Theta(\beta) + \Pi(-\beta,\alpha)\, \Delta\bar{q}(-\beta)\,\Theta(-\beta)\,. \end{aligned}$$

  - chiral-odd sector:

$$f_T^q(\beta,\alpha,t=0) = \Pi(\beta,\alpha)\, \delta q(\beta)\Theta(\beta) - \Pi(-\beta,\alpha)\, \delta\bar{q}(-\beta)\,\Theta(-\beta)\,,$$

  - $\Pi(\beta,\alpha) = \frac{3}{4}\frac{(1-\beta)^2-\alpha^2}{(1-\beta)^3}$: profile function

- simplistic factorized ansatz for the t-dependence:

$$H^q(x,\xi,t) = H^q(x,\xi,t=0)\times F_H(t)$$

with $F_H(t) = \frac{C^2}{(t-C)^2}$ a standard dipole form factor ($C = .71$ GeV)

Model for GPDs: based on the Double Distribution ansatz

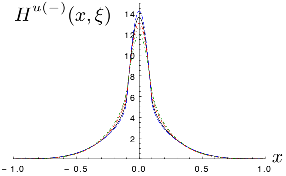
Sets of used PDFs

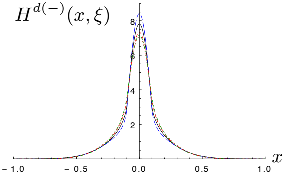
- $q(x)$: unpolarized PDF [GRV-98]
  and [MSTW2008lo, MSTW2008nnlo, ABM11nnlo, CT10nnlo]
- $\Delta q(x)$ polarized PDF [GRSV-2000]
- $\delta q(x)$: transversity PDF [Anselmino *et al.*]

Model for GPDs: based on the Double Distribution ansatz

Typical sets of chiral-even GPDs ($C = -1$ sector)

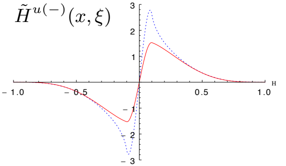
$$\xi = .1 \leftrightarrow S_{\gamma N} = 20 \text{ GeV}^2 \text{ and } M^2_{\gamma\rho} = 3.5 \text{ GeV}^2$$

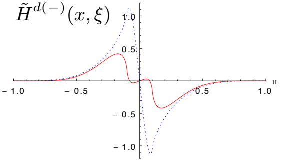




$$H^{q(-)}(x,\xi,t) = H^q(x,\xi,t) + H^q(-x,\xi,t)$$

five Ansätze for $q(x)$: GRV-98, MSTW2008lo, MSTW2008nnlo, ABM11nnlo, CT10nnlo





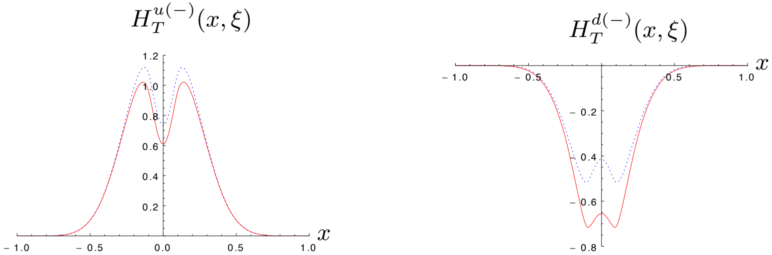
$$\tilde{H}^{q(-)}(x,\xi,t) = \tilde{H}^q(x,\xi,t) - \tilde{H}^q(-x,\xi,t)$$

"valence" and "standard" **(flavor-asymmetries in the polarized antiquark sector are neglected)**:
two GRSV Ansätze for $\Delta q(x)$

Model for GPDs: based on the Double Distribution ansatz

Typical sets of chiral-odd GPDs ($C=-1$ sector)

$$\xi = .1 \leftrightarrow S_{\gamma N} = 20 \text{ GeV}^2 \text{ and } M^2_{\gamma\rho} = 3.5 \text{ GeV}^2$$

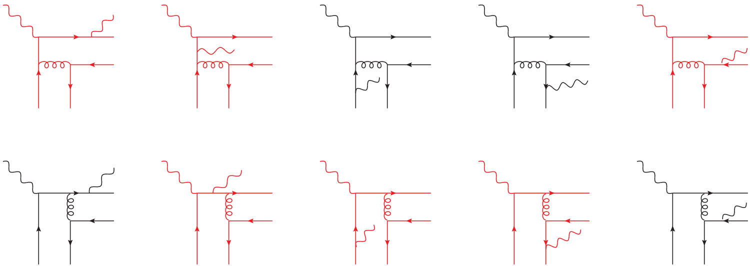


$$H_T^{q(-)}(x,\xi,t) = H_T^q(x,\xi,t) + H_T^q(-x,\xi,t)$$

"valence" and "standard": two GRSV Ansätze for $\Delta q(x)$
$\Rightarrow$ two Ansätze for $\delta q(x)$

Computation of the hard part

20 diagrams to compute



- The other half can be deduced by $q \leftrightarrow \bar{q}$ (anti)symmetry depending on C-parity in $t-$channel
- Red diagrams cancel in the chiral-odd case

Final computation

Final computation

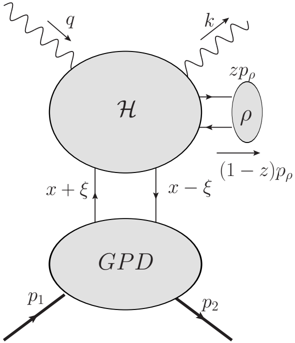
$$\mathcal{A} \propto \int_{-1}^{1} dx \int_{0}^{1} dz\; T(x,\xi,z)\; H(x,\xi,t)\; \Phi_\rho(z)$$

- One performs the z integration analytically using an asymptotic DA $\propto z(1-z)$
- One then plugs our GPD models into the formula and performs the integral w.r.t. x numerically.
- Differential cross section:

$$\left.\frac{d\sigma}{dt\, du'\, dM^2_{\gamma\rho}}\right|_{-t=(-t)_{min}} = \frac{|\overline{\mathcal{M}}|^2}{32 S^2_{\gamma N} M^2_{\gamma\rho} (2\pi)^3}\,.$$

$|\overline{\mathcal{M}}|^2$ = averaged amplitude squared

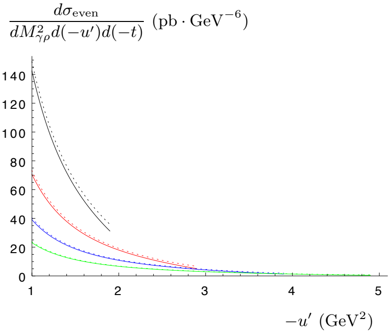
- Kinematical parameters: $S^2_{\gamma N}$, $M^2_{\gamma\rho}$ and $-u'$



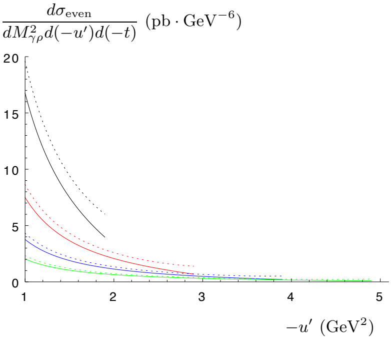
Fully differential cross section: ρ_L

Chiral even cross section

at $-t = (-t)_{\min}$



proton target



neutron target

$$S_{\gamma N} = 20 \text{ GeV}^2$$
$$M^2_{\gamma\rho} = 3, 4, 5, 6 \text{ GeV}^2$$

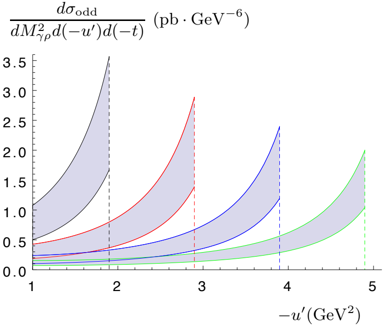
solid: "valence" model

dotted: "standard" model

Fully differential cross section: ρ_T

Chiral odd cross section

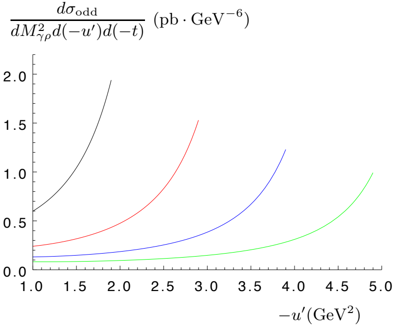
at $-t = (-t)_{\min}$



proton target

"valence" and "standard" models,

each of them with $\pm 2\sigma$ [S. Melis]



neutron target

"valence" model only

$$S_{\gamma N} = 20 \text{ GeV}^2$$
$$M^2_{\gamma\rho} = 3, 4, 5, 6 \text{ GeV}^2$$

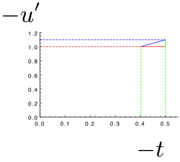
Phase space integration

Evolution of the phase space in $(-t, -u')$ plane

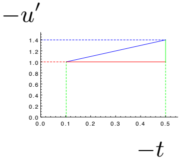
large angle scattering: $M^2_{\gamma\rho} \sim -u' \sim -t'$

in practice: $-u' > 1\ \mathrm{GeV}^2$ and $-t' > 1\ \mathrm{GeV}^2$ and $(-t)_{\min} \leqslant -t \leqslant .5\ \mathrm{GeV}^2$
this ensures large $M^2_{\gamma\rho}$

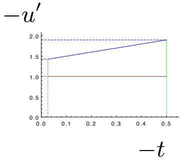
example: $S_{\gamma N} = 20\ \mathrm{GeV}^2$



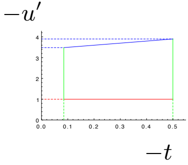
$M_{\gamma\rho} = 2.2\ \mathrm{GeV}^2$



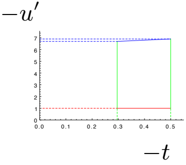
$M^2_{\gamma\rho} = 2.5\ \mathrm{GeV}^2$



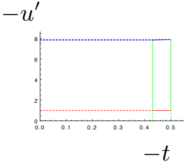
$M_{\gamma\rho} = 3\ \mathrm{GeV}^2$



$M_{\gamma\rho} = 5\ \mathrm{GeV}^2$



$M_{\gamma\rho} = 8\ \mathrm{GeV}^2$



$M_{\gamma\rho} = 9\ \mathrm{GeV}^2$

Variation with respect to $S_{\gamma N}$

Mapping $(S_{\gamma N}, M_{\gamma\rho}) \mapsto (\tilde{S}_{\gamma N}, \tilde{M}_{\gamma\rho})$

One can save a lot of CPU time:

- $\mathcal{M}(\alpha, \xi)$ and $GPDs(\xi, x)$
- In the generalized Bjorken limit:
  - $\alpha = \frac{-u'}{M^2_{\gamma\rho}}$
  - $\xi = \frac{M^2_{\gamma\rho}}{2(S_{\gamma N} - M^2) - M^2_{\gamma\rho}}$

Given $S_{\gamma N}$ ($= 20\ \mathrm{GeV}^2$), with its grid in $M^2_{\gamma\rho}$, choose another $\tilde{S}_{\gamma N}$.
One can get the corresponding grid in $\tilde{M}_{\gamma\rho}$ by just keeping the same ξ's:

$$\tilde{M}^2_{\gamma\rho} = M^2_{\gamma\rho} \frac{\tilde{S}_{\gamma N} - M^2}{S_{\gamma N} - M^2},$$

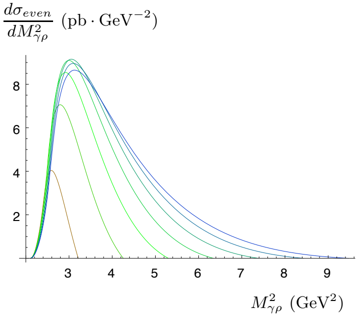
From the grid in $-u'$, the new grid in $-\tilde{u}'$ is given by just keeping the same α's:

$$-\tilde{u}' = \frac{\tilde{M}^2_{\gamma\rho}}{M^2_{\gamma\rho}} (-u').$$

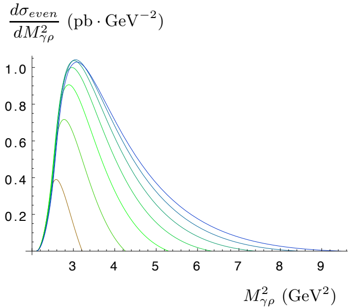
$\Rightarrow$ a single set of numerical computations is required (we take $S_{\gamma N} = 20\ \mathrm{GeV}^2$)

Single differential cross section: ρ_L

Chiral even cross section



proton target



neutron target

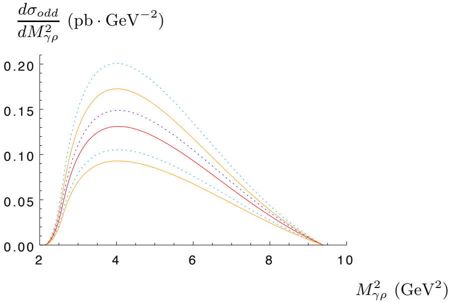
"valence" scenario

$S_{\gamma N}$ vary in the set 8, 10, 12, 14, 16, 18, 20 GeV^2 (from left to right)

typical JLab kinematics

Single differential cross section: ρ_T

Chiral odd cross section



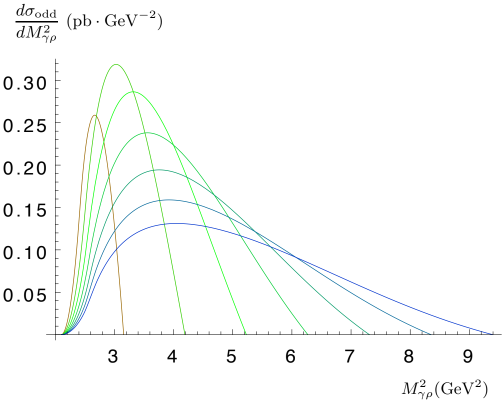
$$S_{\gamma N} = 20 \text{ GeV}^2$$

Various ansätze for the PDFs Δq used to build the GPD H_T:

- *dotted curves*: "standard" scenario
- solid curves: "valence" scenario
- deep-blue and red curves: central values
- light-blue and orange: results with $\pm 2\sigma$.

Single differential cross section: ρ_T

Chiral odd cross section



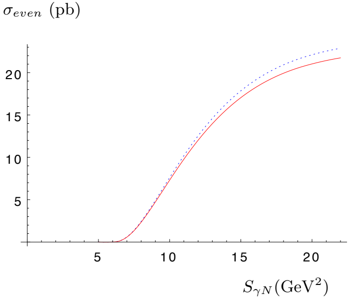
proton target, "valence" scenario

$S_{\gamma N}$ vary in the set 8, 10, 12, 14, 16, 18, 20 GeV^2 (from left to right)

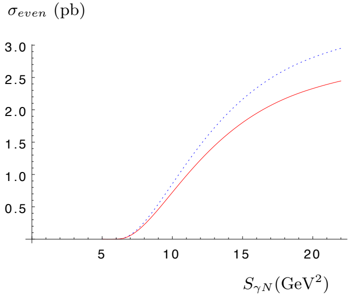
typical JLab kinematics

Integrated cross-section: ρ_L

Chiral even cross section



proton target

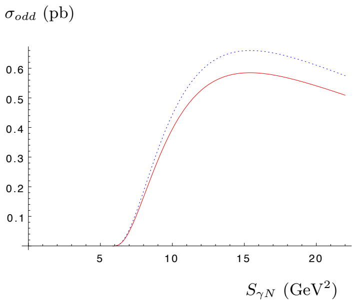


neutron target

solid red: "valence" scenario
dashed blue: "standard" one

Integrated cross-section: ρ_T

Chiral odd cross section



proton target neutron target

solid red: "valence" scenario

dashed blue: "standard" one

Counting rates for 100 days: ρ

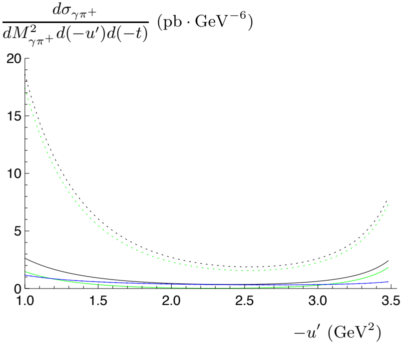
example: JLab Hall B

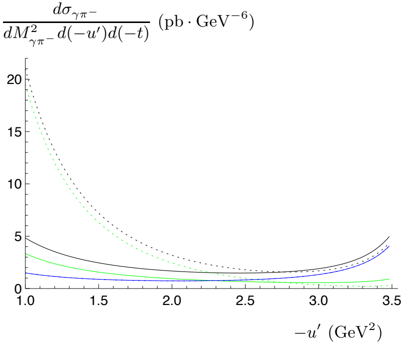
- untagged incoming $\gamma \Rightarrow$ Weizsäcker-Williams distribution
- With an expected luminosity of $\mathcal{L} = 100\ \mathrm{nb}^{-1} s^{-1}$, for 100 days of run:
  - Chiral even case : $\simeq 1.9\ 10^5\ \rho_L$.
  - Chiral odd case : $\simeq 7.5\ 10^3\ \rho_T$

Fully differential cross section: $\pi^{\pm}$

Chiral even sector: $\pi^{\pm}$

at $-t = (-t)_{\min}$





π^+ photoproduction (proton target) π^- photoproduction (neutron target)

$S_{\gamma N} = 20$ GeV^2 $M^2_{\gamma\rho} = 4$ GeV^2

vector GPD / axial GPD / total result

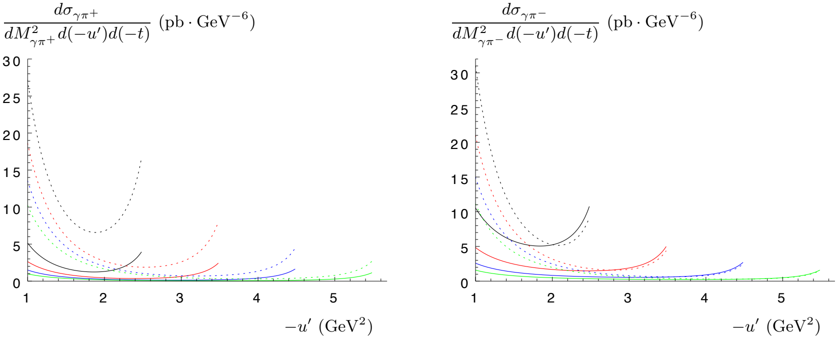
solid: "valence" model

dotted: "standard" model

Fully differential cross section: $\pi^{\pm}$

Chiral even sector: $\pi^{\pm}$

at $-t = (-t)_{\min}$



π^+ photoproduction (proton target) π^- photoproduction (neutron target)

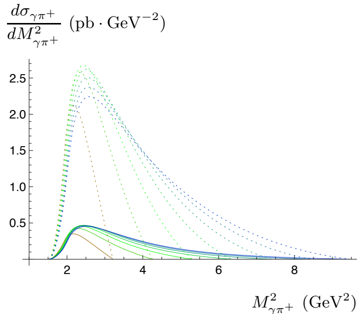
$$S_{\gamma N} = 20\ \mathrm{GeV}^2$$
$$M^2_{\gamma\rho} = 3, 4, 5, 6\ \mathrm{GeV}^2$$

solid: "valence" model

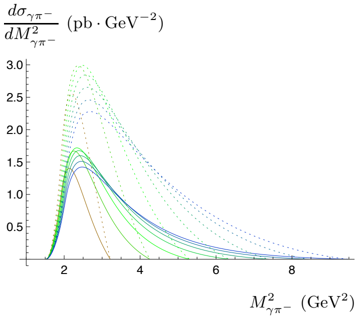
dotted: "standard" model

Single differential cross section: $\pi^{\pm}$

Chiral even sector: $\pi^{\pm}$



π^+ photoproduction (proton target)



π^- photoproduction (neutron target)

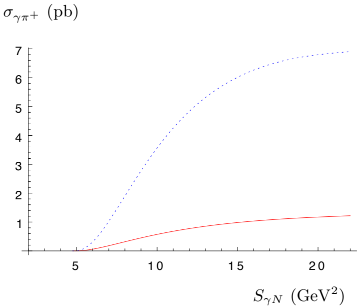
$S_{\gamma N}$ vary in the set 8, 10, 12, 14, 16, 18, 20 GeV^2 (from left to right)

solid: "valence" model

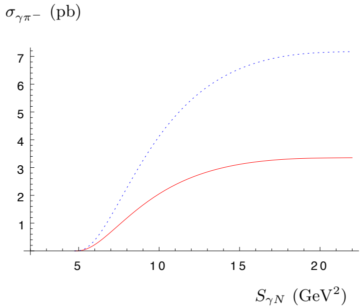
dotted: "standard" model

Integrated cross-section: $\pi^{\pm}$

Chiral even sector: $\pi^{\pm}$



π^+ photoproduction (proton target)



π^- photoproduction (neutron target)

solid red: "valence" scenario

dashed blue: "standard" one

Counting rates for 100 days: $\pi^{\pm}$

example: JLab Hall B

- untagged incoming $\gamma \Rightarrow$ Weizsäcker-Williams distribution
- With an expected luminosity of $\mathcal{L} = 100 \text{ nb}^{-1} s^{-1}$, for 100 days of run:
  - π^+ : $\simeq 10^4$
  - π^- : $\simeq 4 \times 10^4$

Conclusion

Results and experimental perspectives

- High statistics for the chiral-even components: enough to extract H ($\tilde{H}$?) and test the universality of GPDs in ρ^0, $\rho^\pm$ (not shown) and $\pi^\pm$ channels
- In this chiral-even sector: analogy with Timelike Compton Scattering, the $\gamma\rho$ or $\gamma\pi$ pair playing the role of the γ^*.
- ρ-channel: chiral-even component w.r.t. the chiral-odd one:

$$\sigma_{odd}/\sigma_{even} \sim 1/25.$$

  - possible separation ρ_L/ρ_T through an angular analysis of its decay products
  - Future: study of polarization observables $\Rightarrow$ sensitive to the interference of these two amplitudes: very sizable effect expected, of the order of 20%
- The Bethe Heitler component (outgoing γ emitted from the incoming lepton) is:
  - zero for the chiral-odd case
  - suppressed for the chiral-even case
- Possible measurement at JLab (Hall B, C, D)
- A similar study could be performed at COMPASS. EIC, LHC in UPC?

Conclusion

Future

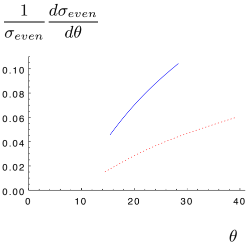
- For $\gamma\pi^{\pm}$ photoproduction:
  - Effect of non asymptotical π DA?
  $$\phi_\pi(z) = \frac{8}{\pi}\sqrt{z(1-z)}$$
  AdS/QCD correspondence, dynamical chiral symmetry breaking on the light-front, etc.
  - Effect of twist 3 contributions? presumably important for π electroproduction
- Observables sensitive to quantum interferences:
  - γ beam asymmetry
  - Target polarization asymmetries
  - For $\rho^0\gamma$ photoproduction: built from the $\pi^+\pi^-$ decay product angular distribution $\Rightarrow$ chiral odd versus chiral even
- Loop corrections: *in progress*
- Accessing GPDs in light nuclei: spin-0 case using an ${}^4He$ target
- Crossed-channel: using the J-PARC π beam (spallation reaction of a proton beam):
  $$\pi N \to \gamma\gamma N$$
- The processes $\gamma N \to \gamma\pi^0 N'$ and $\gamma N \to \gamma\eta^0 N'$ are of particular interest: they give an access to the gluonic GPDs at Born order.
- Our result can also be applied to electroproduction ($Q^2 \neq 0$) after adding Bethe-Heitler contributions and interferences.
- New release of *PARTONS* platform

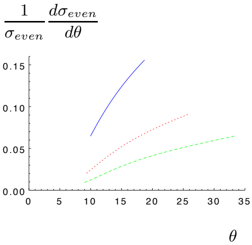
Effects of an experimental angular restriction for the produced γ

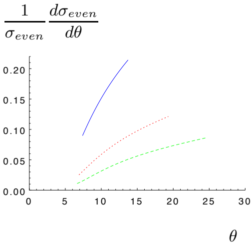
Angular distribution of the produced γ

ρ_L photoproduction

after boosting to the lab frame







$S_{\gamma N} = 10 \text{ GeV}^2$ $\quad$ $S_{\gamma N} = 15 \text{ GeV}^2$ $\quad$ $S_{\gamma N} = 20 \text{ GeV}^2$

$M^2_{\gamma\rho} = 3, 4 \text{ GeV}^2$ $\quad$ $M^2_{\gamma\rho} = 3, 4, 5 \text{ GeV}^2$ $\quad$ $M^2_{\gamma\rho} = 3, 4, 5 \text{ GeV}^2$

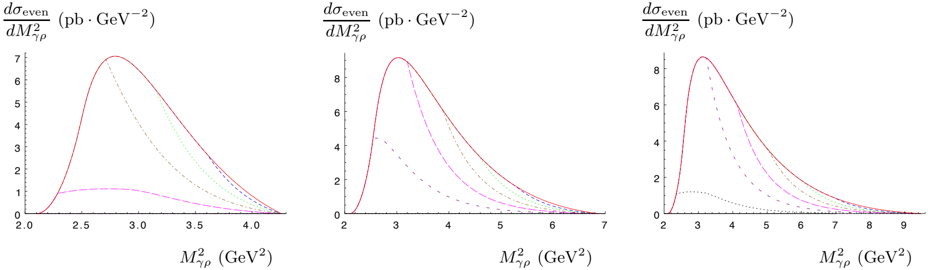
JLab Hall B detector equipped between 5° and 35°

$\Rightarrow$ this is safe!

Effects of an experimental angular restriction for the produced γ

Angular distribution of the produced γ

ρ_L photoproduction



$S_{\gamma N} = 10$ GeV^2 $\quad$ $S_{\gamma N} = 15$ GeV^2 $\quad$ $S_{\gamma N} = 20$ GeV^2

$\theta_{max} = 35°, 30°, 25°, 20°, 15°, 10°$

JLab Hall B detector equipped between 5° and 35°

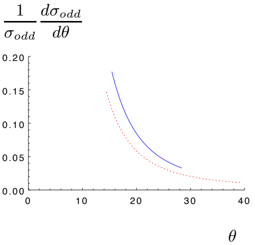
$\Rightarrow$ this is safe!

Effects of an experimental angular restriction for the produced γ

Angular distribution of the produced γ

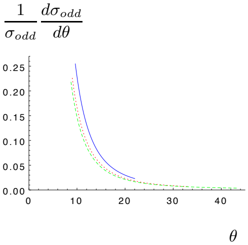
ρ_T photoproduction

after boosting to the lab frame



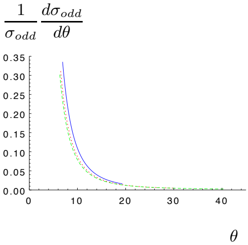
$$S_{\gamma N} = 10 \text{ GeV}^2$$

$$M^2_{\gamma\rho} = 3, 4 \text{ GeV}^2$$



$$S_{\gamma N} = 15 \text{ GeV}^2$$

$$M^2_{\gamma\rho} = 3.5, 5, 6.5 \text{ GeV}^2$$



$$S_{\gamma N} = 20 \text{ GeV}^2$$

$$M^2_{\gamma\rho} = 4, 6, 8 \text{ GeV}^2$$

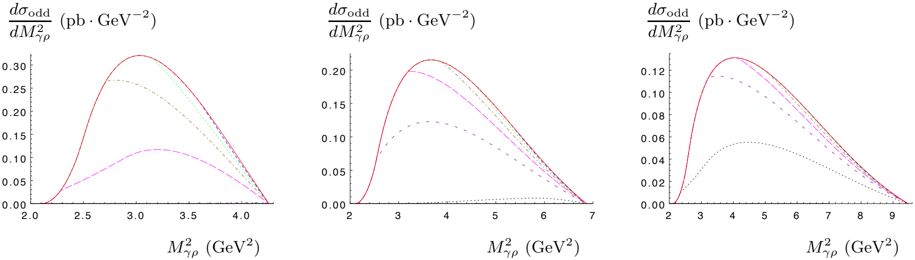
JLab Hall B detector equipped between 5° and 35°

$\Rightarrow$ this is safe!

Effects of an experimental angular restriction for the produced γ

Angular distribution of the produced γ

ρ_T photoproduction



$S_{\gamma N} = 10\ \text{GeV}^2$ $\quad$ $S_{\gamma N} = 15\ \text{GeV}^2$ $\quad$ $S_{\gamma N} = 20\ \text{GeV}^2$

$\theta_{max} = 35°,\ 30°,\ 25°,\ 20°,\ 15°,\ 10°$

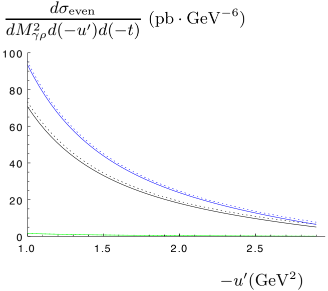
JLab Hall B detector equipped between 5° and 35°

$\Rightarrow$ this is safe!

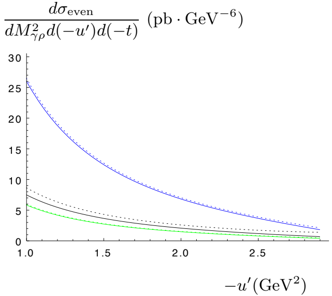
Chiral-even cross section

Contribution of u versus d

ρ_L photoproduction



proton



neutron

$M^2_{\gamma\rho} = 4\ \text{GeV}^2$. Both vector and axial GPDs are included.

$u + d$ quarks u quark d quark

Solid: "valence" model

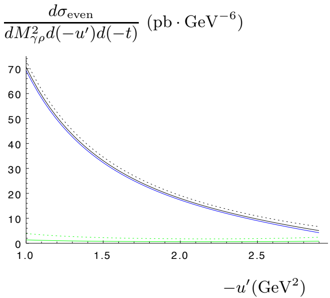
dotted: "standard" model

- u-quark contribution dominates due to the charge effect
- the interference between u and d contributions is important and negative.

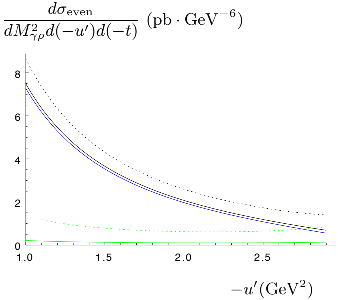
Chiral-even cross section

Contribution of vector versus axial amplitudes

ρ_L photoproduction



proton



neutron

$M^2_{\gamma\rho} = 4\ \text{GeV}^2$. Both u and d quark contributions are included.

vector + axial amplitudes / vector amplitude / axial amplitude

solid: "valence" model

dotted: "standard" model

- dominance of the vector GPD contributions
- no interference between the vector and axial amplitudes

Gluon GPDs in the UPC production of heavy mesons

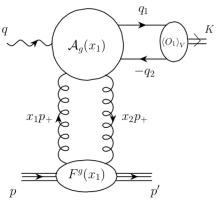


Figure 1: Kinematics of heavy vector meson photoproduction.

D. Yu. Ivanov , A. Schafer , L. Szymanowski and G. Krasnikov - **Eur.Phys.J. C34 (2004) 297-316**

The amplitude $\mathcal{M}$ is given by factorization formula:

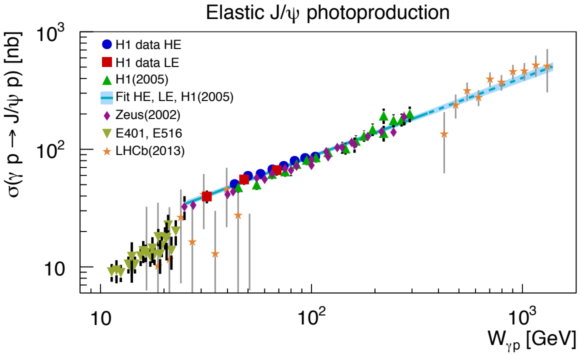
$$\mathcal{M} \quad \sim \quad \left(\frac{\langle O_1 \rangle_V}{m^3} \right)^{1/2} \int\limits_{-1}^{1} dx \left[T_g(x,\xi)\, F^g(x,\xi,t) + T_q(x,\xi) F^{q,S}(x,\xi,t) \right] ,$$

$$F^{q,S}(x,\xi,t) \quad = \quad \sum_{q=u,d,s} F^q(x,\xi,t) \, .$$

where m is a pole mass of heavy quark, $\langle O_1 \rangle_V$ is given by NRQCD through leptonic meson decay rate.

Heavy Vector Mesons Photoproduction

We have good data! See H1 2013 paper:



Photoproduction cross section - LO and NLO

Work with D.Yu.Ivanov and J. Wagner

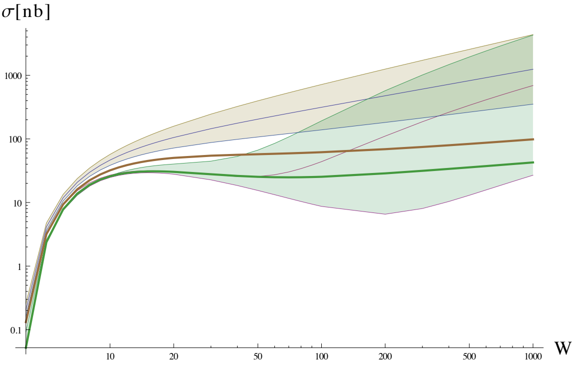
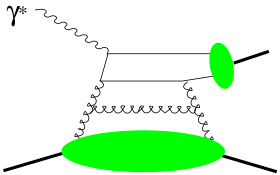


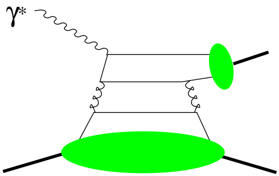
Figure: Photoproduction cross section as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2 \times \{0.5, 1, 2\}$- LO and NLO. Thick lines for LO and NLO for $\mu_F^2 = 1/4 M_{J/\psi}^2$.

- Jones & Martin & Ryskin & Teubner, arXiv:1507.06942. Choice of the factorization scale.
- Why NLO corrections are large at small x_B?
  large contribution comes from

$$ImA^g \sim H^g(\xi,\xi) + \frac{3\alpha_s}{\pi}\left[\log\frac{M_V^2}{\mu_F^2} - \log 4\right]\int_\xi^1 \frac{dx}{x} H^g(x,\xi)$$

$H^g(x,\xi) \sim xg(x) \sim const$, therefore $\int dx/x H^g(x,\xi) \sim \log(1/\xi) H^g(\xi,\xi)$

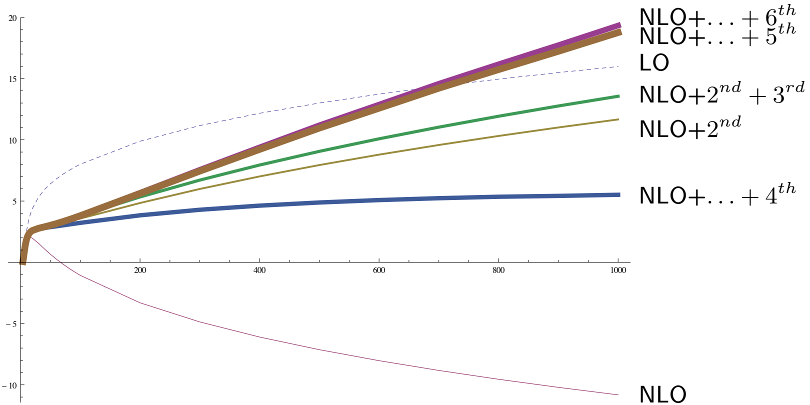




Resummed amplitude for J/ψ

S. Catani and F. Hautmann, Nucl. Phys. B 427 (1994) 475. for DIS

$$ImA^g \sim H^g(\xi,\xi) + \int_{2\xi}^1 \frac{dx}{x} H^g(x,\xi) \sum_{n=1} C_n(L) \frac{\bar{\alpha}_s^n}{(n-1)!} \log^{n-1} \frac{x}{\xi}$$



Imaginary part of the amplitude for photoproduction of heavy mesons as a function of $W = \sqrt{s_{\gamma p}}$ for $\mu_F^2 = M_{J/\psi}^2$