

Photon-meson pair photoproduction: a new way to probe Generalized Parton Distributions

Samuel Wallon

Sorbonne Université

and

Laboratoire de Physique Théorique

CNRS / Université Paris Sud

Orsay

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in collaboration with

B. Pire (CPHT, Palaiseau), R. Boussarie (LPT Orsay), L. Szymanowski (NCBJ, Warsaw), G. Duplančić, K. Passek-Kumerički (IRB, Zagreb)

based on:

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

JHEP 18xx (2017) xx [arXiv:1809.08104 [hep-ph]] ($\pi\gamma$ production)

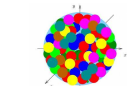
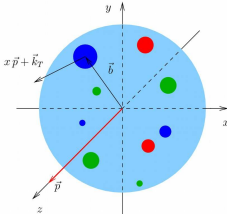
The ultimate picture

6D/5D

Wigner distributions for hadrons

$$W(x, \vec{b}, k_T)$$

Experimentally inaccessible directly

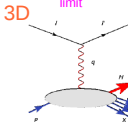


3D perturbative Regge limit

uPDFs (gluons)

Unintegrated parton distributions

$$\int d^3 \vec{b}$$



Semi-inclusive processes

Transverse momentum dependent distributions

TMDs $f(x, k_T)$

$$\int d^2 k_T \int d b_z$$

Impact parameter distributions $f(x, b_T)$

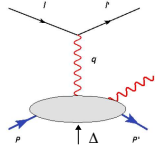
Impact parameter distributions

$$b_T \leftrightarrow \Delta \quad H(x, 0, t) \quad t = -\Delta^2$$

$$\int d^2 k_T \int \text{Fourier}(\vec{b})$$

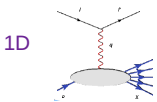
generalised parton distributions $H(x, \xi, t)$

generalised parton distributions



exclusive processes

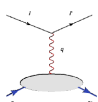
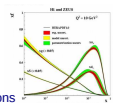
1D



inclusive and semi-inclusive processes

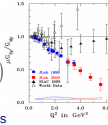
PDFs $f(x)$

parton distributions



elastic processes

FFs $G_{E,M}(t)$ form factors



GFFs

generalized form factors

lattices

Extensions from DIS

- DIS: inclusive process \rightarrow forward amplitude ($t = 0$) (optical theorem)

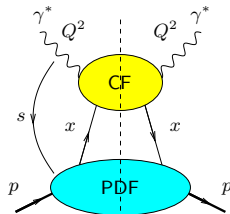
(DIS: Deep Inelastic Scattering)

ex: $e^\pm p \rightarrow e^\pm X$ at HERA

$x \Rightarrow$ 1-dimensional structure

Structure Function

$$= \text{Coefficient Function (hard)} \otimes \text{Parton Distribution Function (soft)}$$



- DVCS: exclusive process \rightarrow non forward amplitude ($-t \ll s = W^2$)

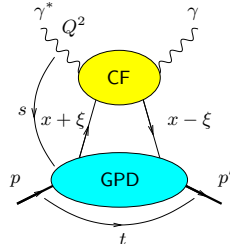
(DVCS: Deep Virtual Compton Scattering)

Fourier transf.: $t \leftrightarrow$ impact parameter

$(x, t) \Rightarrow$ 3-dimensional structure

Amplitude

$$= \text{Coefficient Function (hard)} \otimes \text{Generalized Parton Distribution (soft)}$$

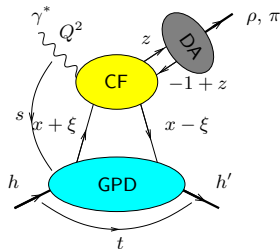


Müller et al. '91 - '94; Radyushkin '96; Ji '97

Extensions from DVCS

- **Meson production:** γ replaced by ρ, π, \dots

$$\begin{aligned}
 & \text{Amplitude} \\
 = & \quad \text{GPD (soft)} \quad \otimes \quad \text{CF (hard)} \quad \otimes \quad \text{Distribution Amplitude (soft)}
 \end{aligned}$$



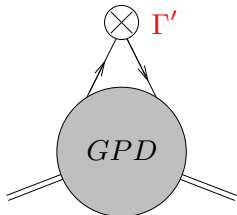
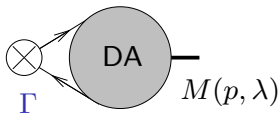
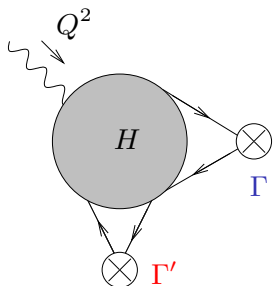
Collins, Frankfurt, Strikman '97; Radyushkin '97

proofs valid only for some restricted cases

Collinear factorization

Meson electroproduction: factorization with a GPD and a DA

The building blocks



Γ, Γ' : Dirac matrices compatible
with quantum numbers: $C, P, T, \text{chirality}$

Similar structure for gluon exchange

Collinear factorization

Twist 2 GPDs

Classification of twist 2 GPDs

- For quarks, one should distinguish the exchanges
 - without helicity flip (chiral-even Γ' matrices): 4 chiral-even GPDs:

$$H^q \xrightarrow{\xi=0, t=0} \text{PDF } q, E^q, \tilde{H}^q \xrightarrow{\xi=0, t=0} \text{polarized PDFs } \Delta q, \tilde{E}^q$$

$$\begin{aligned} F^q &= \frac{1}{2} \int \frac{dz^+}{2\pi} e^{ixP^+z^-} \langle p' | \bar{q}(-\frac{1}{2}z) \gamma^+ q(\frac{1}{2}z) | p \rangle \Big|_{z^+=0, z_\perp=0} \\ &= \frac{1}{2P^+} \left[H^q(x, \xi, t) \bar{u}(p') \gamma^+ u(p) + E^q(x, \xi, t) \bar{u}(p') \frac{i\sigma^{+\alpha} \Delta_\alpha}{2m} u(p) \right], \end{aligned}$$

$$\begin{aligned} \tilde{F}^q &= \frac{1}{2} \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p' | \bar{q}(-\frac{1}{2}z) \gamma^+ \gamma_5 q(\frac{1}{2}z) | p \rangle \Big|_{z^+=0, z_\perp=0} \\ &= \frac{1}{2P^+} \left[\tilde{H}^q(x, \xi, t) \bar{u}(p') \gamma^+ \gamma_5 u(p) + \tilde{E}^q(x, \xi, t) \bar{u}(p') \frac{\gamma_5 \Delta^+}{2m} u(p) \right]. \end{aligned}$$

- with helicity flip (chiral-odd Γ' mat.): 4 chiral-odd GPDs:

$$H_T^q \xrightarrow{\xi=0, t=0} \text{quark transversity PDFs } \delta q, E_T^q, \tilde{H}_T^q, \tilde{E}_T^q$$

$$\begin{aligned} &\frac{1}{2} \int \frac{dz^-}{2\pi} e^{ixP^+z^-} \langle p' | \bar{q}(-\frac{1}{2}z) i\sigma^{+i} q(\frac{1}{2}z) | p \rangle \Big|_{z^+=0, z_\perp=0} \\ &= \frac{1}{2P^+} \bar{u}(p') \left[H_T^q i\sigma^{+i} + \tilde{H}_T^q \frac{P^+ \Delta^i - \Delta^+ P^i}{m^2} + E_T^q \frac{\gamma^+ \Delta^i - \Delta^+ \gamma^i}{2m} + \tilde{E}_T^q \frac{\gamma^+ P^i - P^+ \gamma^i}{m} \right] \end{aligned}$$

Collinear factorization

Twist 2 GPDs

Classification of twist 2 GPDs

- analogously, for gluons:

- 4 gluonic GPDs without helicity flip:

$$\begin{matrix} H^g \\ E^g \end{matrix} \xrightarrow{\xi=0, t=0} \text{PDF } x g$$

$$\begin{matrix} \tilde{H}^g \\ \tilde{E}^g \end{matrix} \xrightarrow{\xi=0, t=0} \text{polarized PDF } x \Delta g$$

- 4 gluonic GPDs with helicity flip:

$$\begin{matrix} H_T^g \\ E_T^g \\ \tilde{H}_T^g \\ \tilde{E}_T^g \end{matrix}$$

(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

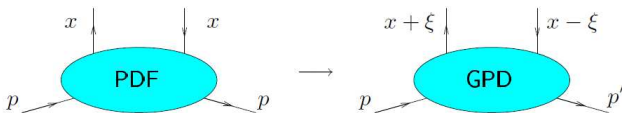
What is transversity?

- Transverse spin content of the proton:

$$\begin{aligned} |\uparrow\rangle(x) &\sim |\rightarrow\rangle + |\leftarrow\rangle \\ |\downarrow\rangle(x) &\sim |\rightarrow\rangle - |\leftarrow\rangle \end{aligned}$$

spin along x helicity states

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

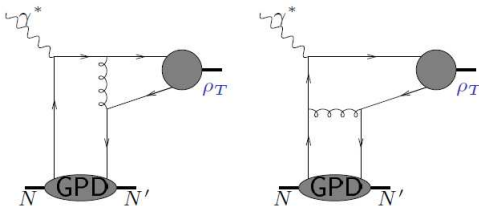


- For massless (anti)particles, chirality = (-)helicity
- **Transversity is thus a chiral-odd quantity**
- Since (in the massless limit) QCD and QED are chiral-even ($\gamma^\mu, \gamma^\mu \gamma^5$), **the chiral-odd quantities ($1, \gamma^5, [\gamma^\mu, \gamma^\nu]$) which one wants to measure should 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 $\gamma^* N^\uparrow \rightarrow \rho_T N' = 0$
 - This cancellation is true at any order : such a process would require a helicity transfer of 2 from a photon.
 - lowest order diagrammatic argument:



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

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

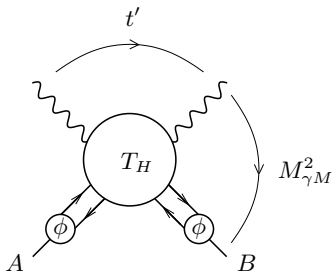
Transversity of the nucleon using hard processes: using a two body final state process?

Can one circumvent this vanishing?

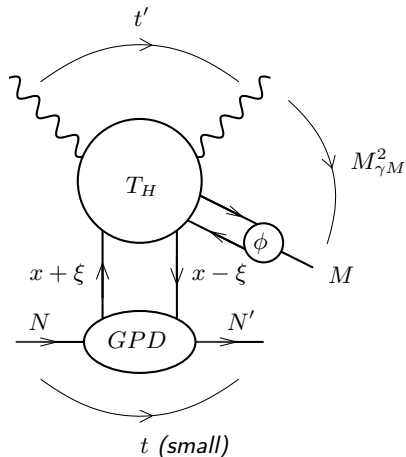
- This vanishing only occurs at **twist 2**
- At twist 3 this process does not vanish [Ahmad, Goldstein, Liuti], [Goloskokov, Kroll]
- However processes involving **twist 3 DAs** may face problems with factorization (end-point singularities)
can be made safe in the high-energy k_T -factorization approach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

Probing GPDs using ρ or π meson + photon production

- We consider the process $\gamma N \rightarrow \gamma M N'$ $M = \text{meson}$
- Collinear factorization of the amplitude for $\gamma + N \rightarrow \gamma + M + N'$ at large $M_{\gamma M}^2$

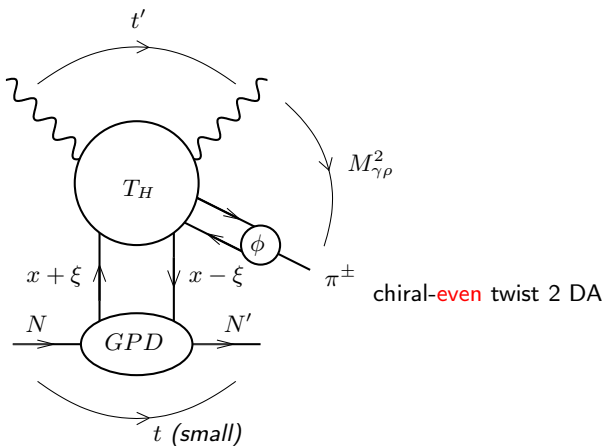


large angle factorization
à la Brodsky Lepage



Probing **chiral-even** GPDs using π meson + photon production

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

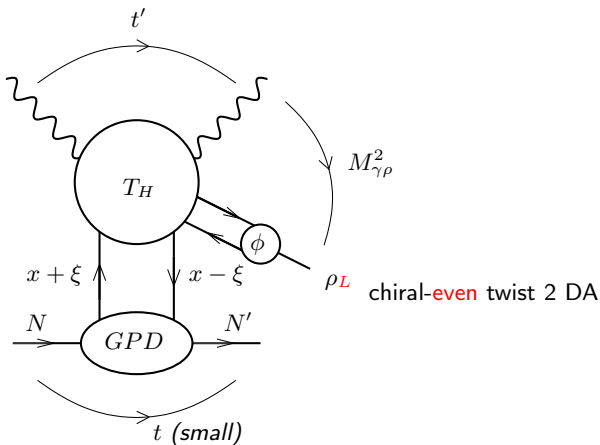


chiral-even twist 2 DA

chiral-even twist 2 GPD

Probing **chiral-even** GPDs using ρ meson + photon production

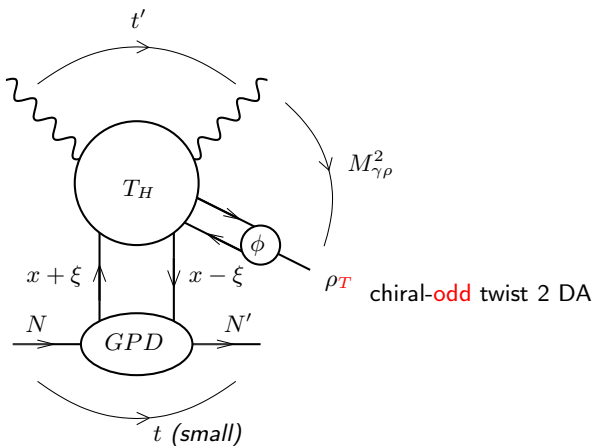
Processes with **3 body final states** can give access to **chiral-even GPDs**



chiral-even twist 2 GPD

Probing chiral-odd GPDs using ρ meson + photon production

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

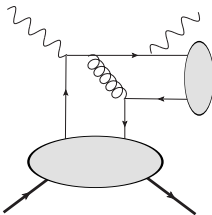


chiral-odd twist 2 GPD

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 $2 \rightarrow 2$ processes?



Typical non-zero diagram for a **transverse** ρ meson

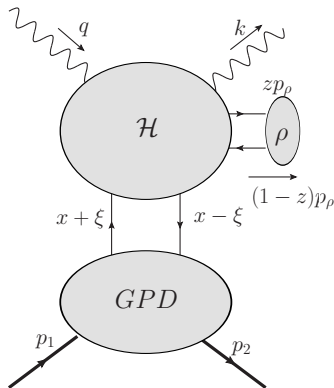
the σ matrices (from DA and GPD sides) do not kill it anymore!

Master formula based on leading twist 2 factorization

The ρ example

$$\mathcal{A} \propto \int_{-1}^1 dx \int_0^1 dz T(x, \xi, z) \times H(x, \xi, t) \Phi_\rho(z) + \dots$$

- 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 $2p \cdot n = s$
- assume the following kinematics:
 - $\Delta_{\perp} \ll p_{\perp}$
 - $M^2, m_{\rho}^2 \ll M_{\gamma\rho}^2$

- initial state particle momenta:

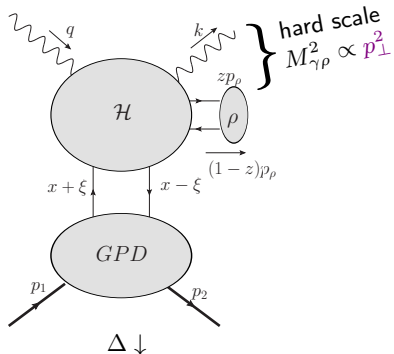
$$q^{\mu} = n^{\mu}, \quad p_1^{\mu} = (1 + \xi) p^{\mu} + \frac{M^2}{s(1+\xi)} n^{\mu}$$

- final state particle momenta:

$$p_2^{\mu} = (1 - \xi) p^{\mu} + \frac{M^2 + \vec{p}_t^2}{s(1 - \xi)} n^{\mu} + \Delta_{\perp}^{\mu}$$

$$k^{\mu} = \alpha n^{\mu} + \frac{(\vec{p}_t - \vec{\Delta}_t/2)^2}{\alpha s} p^{\mu} + p_{\perp}^{\mu} - \frac{\Delta_{\perp}^{\mu}}{2},$$

$$p_{\rho}^{\mu} = \alpha_{\rho} n^{\mu} + \frac{(\vec{p}_t + \vec{\Delta}_t/2)^2 + m_{\rho}^2}{\alpha_{\rho} s} p^{\mu} - p_{\perp}^{\mu} - \frac{\Delta_{\perp}^{\mu}}{2},$$



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 and in the forward limit $\xi \rightarrow 0$ 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 :

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

- We will consider the simplest case when $\Delta_\perp = 0$.
- In that case and in the forward limit $\xi \rightarrow 0$ 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):

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

- 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:

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

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

- 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

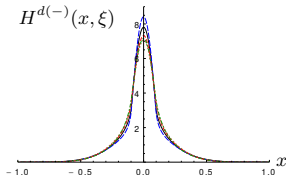
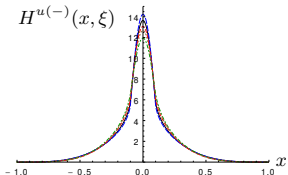
Sets of used PDFs

- $q(x)$: 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

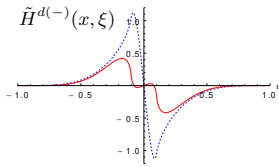
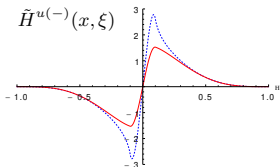
Typical sets of chiral-even GPDs ($C = -1$ sector)

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



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

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



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

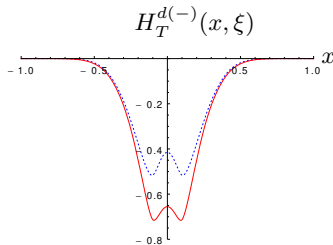
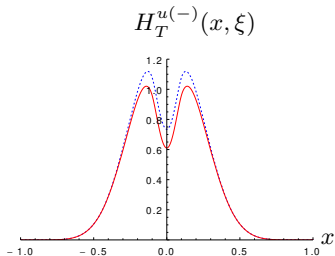
“valence” and “standard” (flavor-asymmetries in the polarized antiquark sector are neglected):

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)

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



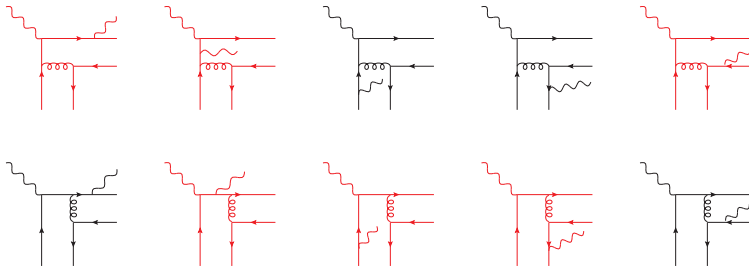
$$H_T^{q(-)}(x, \xi, t) = H_T^q(x, \xi, t) + H_T^q(-x, \xi, t)$$

“valence” and “standard”: two GRSV Ansätze for $\Delta q(x)$

⇒ 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

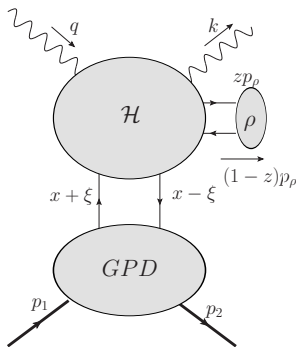
$$\mathcal{A} \propto \int_{-1}^1 dx \int_0^1 dz T(x, \xi, z) H(x, \xi, t) \Phi_\rho(z)$$

- 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:

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

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

- Kinematical parameters: $S_{\gamma N}^2$, $M_{\gamma\rho}^2$ and $-u'$

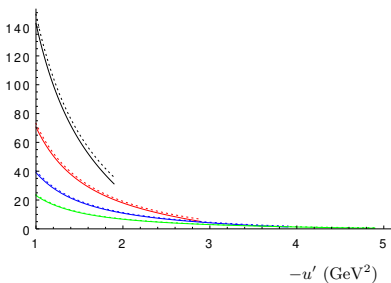


Fully differential cross section: ρ_L

Chiral even cross section

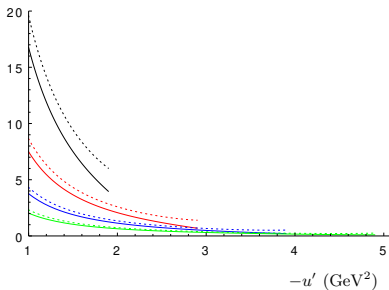
at $-t = (-t)_{\min}$

$$\frac{d\sigma_{\text{even}}}{dM_{\gamma\rho}^2 d(-u') d(-t)} \text{ (pb} \cdot \text{GeV}^{-6}\text{)}$$



proton target

$$\frac{d\sigma_{\text{even}}}{dM_{\gamma\rho}^2 d(-u') d(-t)} \text{ (pb} \cdot \text{GeV}^{-6}\text{)}$$



neutron target

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

$$M_{\gamma\rho}^2 = 3, 4, 5, 6 \text{ GeV}^2$$

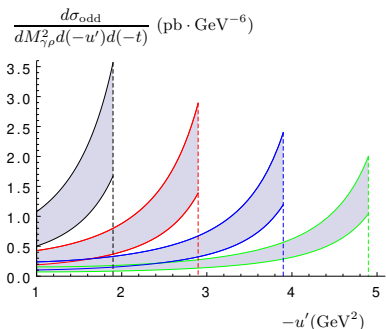
solid: "valence" model

dotted: "standard" model

Fully differential cross section: ρ_T

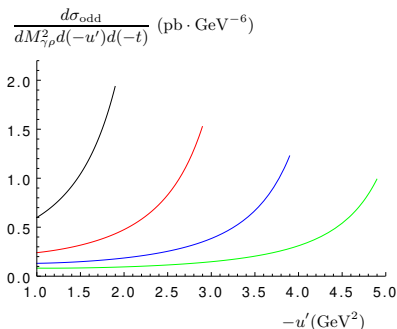
Chiral odd cross section

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



proton target

"valence" and "standard" models,
each of them with $\pm 2\sigma$ [S. Melis]



neutron target

"valence" model only

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

$$M_{\gamma\rho}^2 = 3, 4, 5, 6 \text{ GeV}^2$$

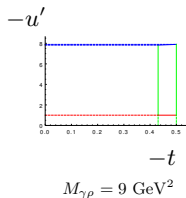
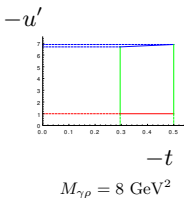
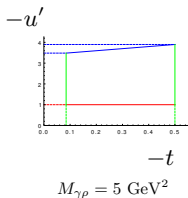
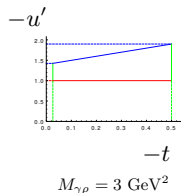
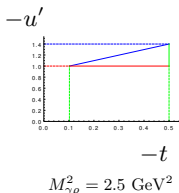
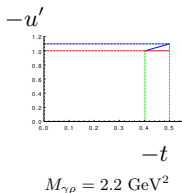
Phase space integration

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

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

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

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



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

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

One can save a lot of CPU time:

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

Given $S_{\gamma N}$ ($= 20 \text{ GeV}^2$), with its grid in $M_{\gamma\rho}^2$, choose another $\tilde{S}_{\gamma N}$.

One can get the corresponding grid in $\tilde{M}_{\gamma\rho}$ by just keeping the same ξ 's:

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

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

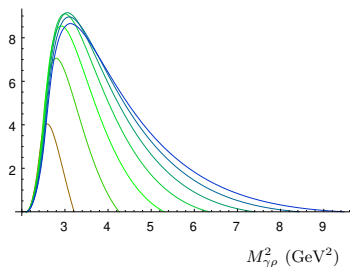
$$-\tilde{u}' = \frac{\tilde{M}_{\gamma\rho}^2}{M_{\gamma\rho}^2} (-u').$$

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

Single differential cross section: ρ_L

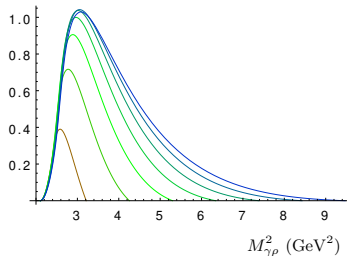
Chiral even cross section

$$\frac{d\sigma_{even}}{dM_{\gamma\rho}^2} \text{ (pb} \cdot \text{GeV}^{-2}\text{)}$$



proton target

$$\frac{d\sigma_{even}}{dM_{\gamma\rho}^2} \text{ (pb} \cdot \text{GeV}^{-2}\text{)}$$



neutron target

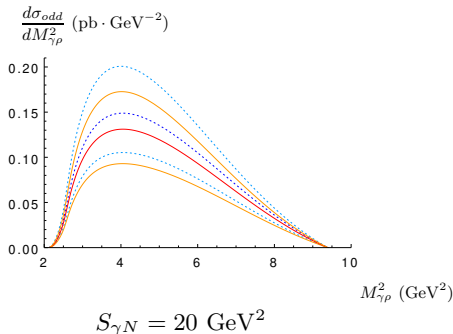
"valence" scenario

$S_{\gamma N}$ vary in the set 8, 10, 12, 14, 16, 18, 20 GeV² (from left to right)

typical JLab kinematics

Single differential cross section: ρ_T

Chiral odd cross section

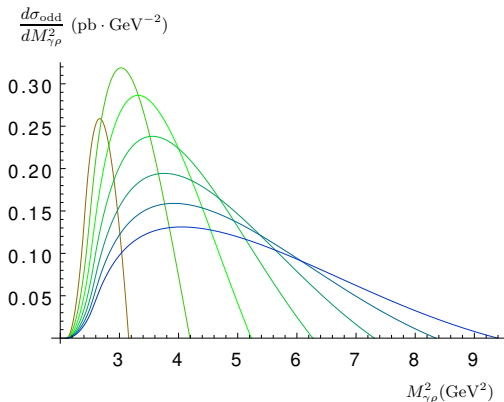


Various ansätze for the PDFs Δq used to build the GPD H_T :

- *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



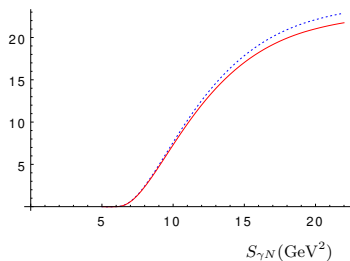
proton target, "valence" scenario

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

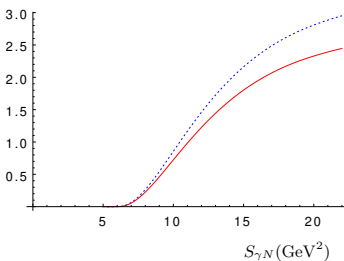
typical JLab kinematics

Integrated cross-section: ρ_L

Chiral even cross section

 σ_{even} (pb)

proton target

 σ_{even} (pb)

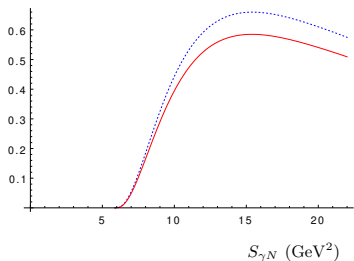
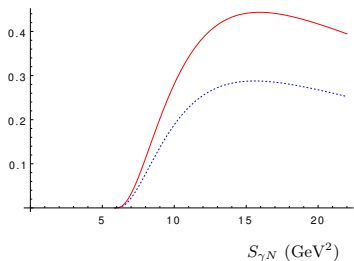
neutron target

solid red: "valence" scenario

dashed blue: "standard" one

Integrated cross-section: ρ_T

Chiral odd cross section

 σ_{odd} (pb) σ_{odd} (pb)

solid red: "valence" scenario

dashed blue: "standard" one

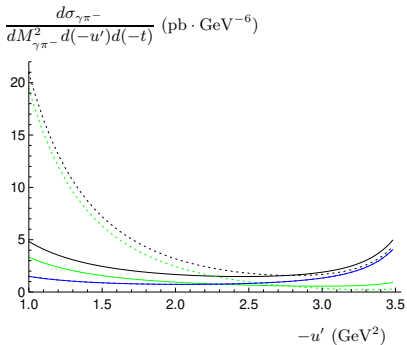
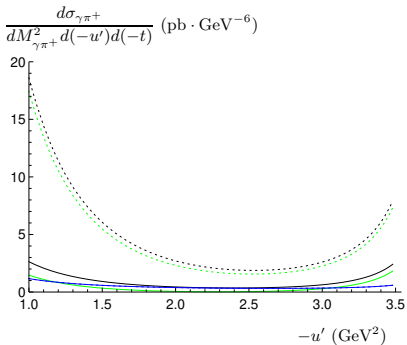
Counting rates for 100 days: ρ

example: JLab Hall B

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

Fully differential cross section: π^\pm

Chiral even sector: π^\pm
at $-t = (-t)_{\min}$



π^+ photoproduction (proton target)

π^- photoproduction (neutron target)

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

$$M_{\gamma p}^2 = 4 \text{ GeV}^2$$

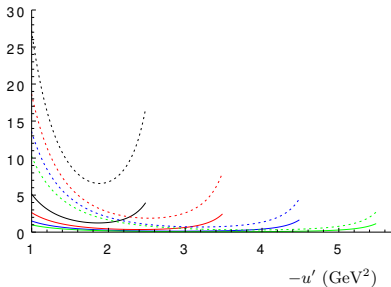
vector GPD / axial GPD / total result

solid: "valence" model

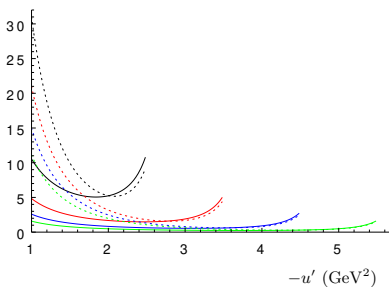
dotted: "standard" model

Fully differential cross section: π^\pm Chiral even sector: π^\pm at $-t = (-t)_{\min}$

$$\frac{d\sigma_{\gamma\pi^+}}{dM_{\gamma\pi^+}^2 d(-u')d(-t)} \text{ (pb} \cdot \text{GeV}^{-6}\text{)}$$

 π^+ photoproduction (proton target)

$$\frac{d\sigma_{\gamma\pi^-}}{dM_{\gamma\pi^-}^2 d(-u')d(-t)} \text{ (pb} \cdot \text{GeV}^{-6}\text{)}$$

 π^- photoproduction (neutron target)

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

$$M_{\gamma\rho}^2 = 3, 4, 5, 6 \text{ GeV}^2$$

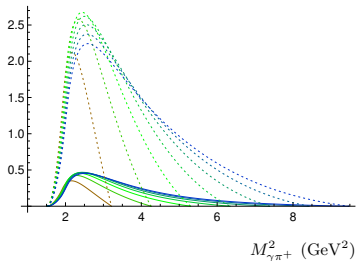
solid: "valence" model

dotted: "standard" model

Single differential cross section: π^\pm

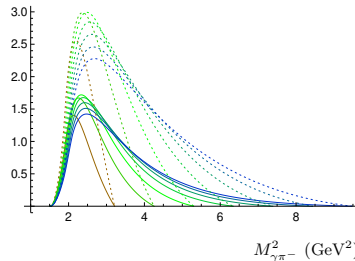
Chiral even sector: π^\pm

$$\frac{d\sigma_{\gamma\pi^+}}{dM^2_{\gamma\pi^+}} \text{ (pb} \cdot \text{GeV}^{-2}\text{)}$$



π^+ photoproduction (proton target)

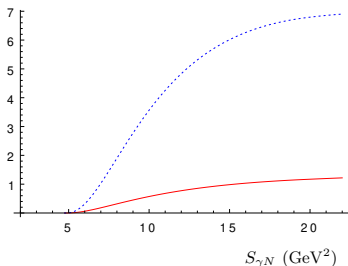
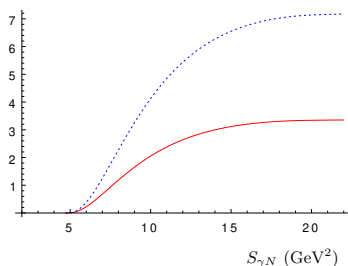
$$\frac{d\sigma_{\gamma\pi^-}}{dM^2_{\gamma\pi^-}} \text{ (pb} \cdot \text{GeV}^{-2}\text{)}$$



π^- photoproduction (neutron target)

$S_{\gamma N}$ vary in the set 8, 10, 12, 14, 16, 18, 20 GeV² (from left to right)

solid: "valence" model
dotted: "standard" model

Integrated cross-section: π^\pm Chiral even sector: π^\pm $\sigma_{\gamma\pi^+}$ (pb) $\sigma_{\gamma\pi^-}$ (pb) π^+ photoproduction (proton target) π^- photoproduction (neutron target)

solid red: "valence" scenario

dashed blue: "standard" one

Counting rates for 100 days: π^\pm

example: JLab Hall B

- untagged incoming $\gamma \Rightarrow$ Weizsäcker-Williams distribution
- With an expected luminosity of $\mathcal{L} = 100 \text{ nb}^{-1} \text{ s}^{-1}$, 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 , ρ^\pm (not shown) and π^\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:

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

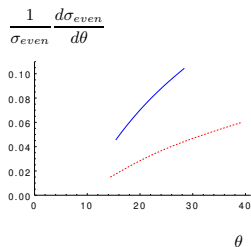
- Effect of twist 3 contributions? presumably important for π electroproduction
- Observables sensitive to quantum interferences:
 - γ beam asymmetry
 - Target polarization asymmetries
 - For $\rho^0\gamma$ photoproduction: built from the $\pi^+\pi^-$ decay product angular distribution \Rightarrow chiral 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):

$$\pi N \rightarrow \gamma\gamma N$$

- The processes $\gamma N \rightarrow \gamma\pi^0 N'$ and $\gamma N \rightarrow \gamma\eta^0 N'$ 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

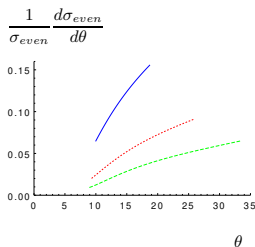
Effects of an experimental angular restriction for the produced γ Angular distribution of the produced γ
 ρ_L photoproduction

after boosting to the lab frame



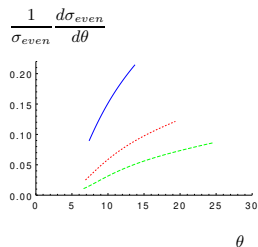
$$S_{\gamma N} = 10 \text{ GeV}^2$$

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



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

$$M_{\gamma\rho}^2 = 3, 4, 5 \text{ GeV}^2$$



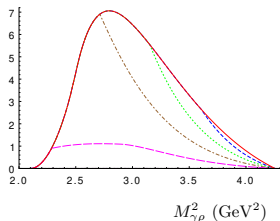
$$S_{\gamma N} = 20 \text{ GeV}^2$$

$$M_{\gamma\rho}^2 = 3, 4, 5 \text{ GeV}^2$$

JLab Hall B detector equipped between 5° and 35° \Rightarrow this is safe!

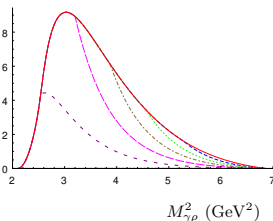
Effects of an experimental angular restriction for the produced γ Angular distribution of the produced γ
 ρ_L photoproduction

$$\frac{d\sigma_{\text{even}}}{dM_{\gamma\rho}^2} \text{ (pb} \cdot \text{GeV}^{-2}\text{)}$$



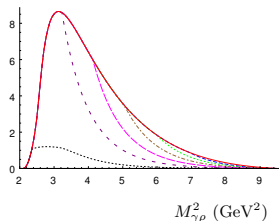
$$S_{\gamma N} = 10 \text{ GeV}^2$$

$$\frac{d\sigma_{\text{even}}}{dM_{\gamma\rho}^2} \text{ (pb} \cdot \text{GeV}^{-2}\text{)}$$



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

$$\frac{d\sigma_{\text{even}}}{dM_{\gamma\rho}^2} \text{ (pb} \cdot \text{GeV}^{-2}\text{)}$$



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

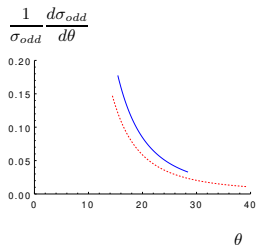
$$\theta_{\text{max}} = 35^\circ, 30^\circ, 25^\circ, 20^\circ, 15^\circ, 10^\circ$$

JLab Hall B detector equipped between 5° and 35°

\Rightarrow this is safe!

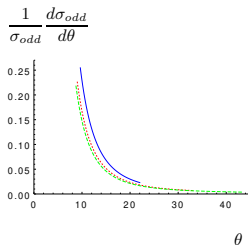
Effects of an experimental angular restriction for the produced γ Angular distribution of the produced γ
 ρ_T photoproduction

after boosting to the lab frame



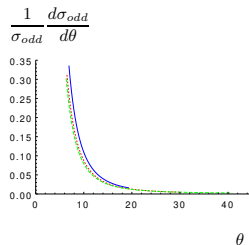
$$S_{\gamma N} = 10 \text{ GeV}^2$$

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



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

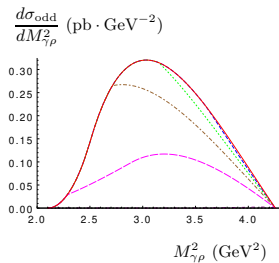
$$M_{\gamma\rho}^2 = 3.5, 5, 6.5 \text{ GeV}^2$$



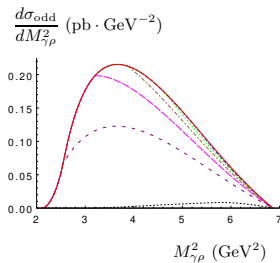
$$S_{\gamma N} = 20 \text{ GeV}^2$$

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

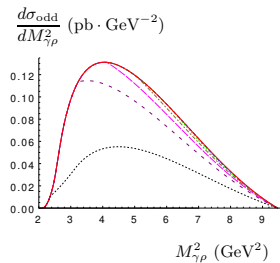
JLab Hall B detector equipped between 5° and 35° \Rightarrow this is safe!

Effects of an experimental angular restriction for the produced γ Angular distribution of the produced γ
 ρ_T photoproduction

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



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



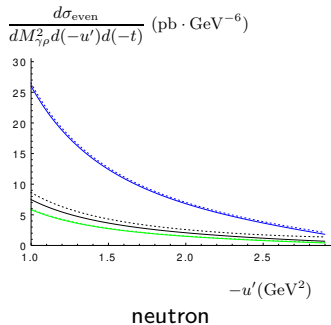
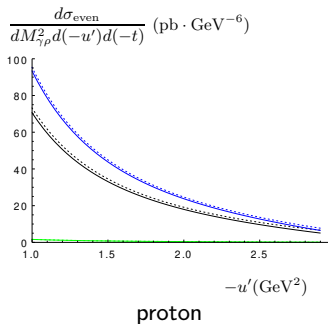
$$S_{\gamma N} = 20 \text{ GeV}^2$$

$$\theta_{\text{max}} = 35^\circ, 30^\circ, 25^\circ, 20^\circ, 15^\circ, 10^\circ$$

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

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

$u + d$ quarks u quark d quark

Solid: "valence" model

dotted: "standard" model

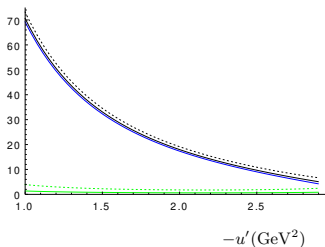
- u -quark contribution dominates due to the charge effect
- the interference between u and d contributions is important and negative.

Chiral-even cross section

Contribution of vector versus axial amplitudes

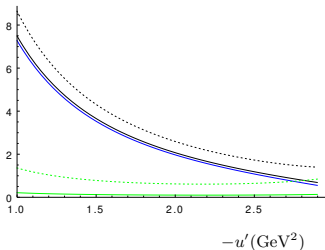
 ρ_L photoproduction

$$\frac{d\sigma_{\text{even}}}{dM_{\gamma\rho}^2 d(-u')d(-t)} \text{ (pb} \cdot \text{GeV}^{-6}\text{)}$$



proton

$$\frac{d\sigma_{\text{even}}}{dM_{\gamma\rho}^2 d(-u')d(-t)} \text{ (pb} \cdot \text{GeV}^{-6}\text{)}$$



neutron

$M_{\gamma\rho}^2 = 4 \text{ GeV}^2$. 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