Exclusive photoproduction of a $\gamma\rho$ pair with a large invariant mass

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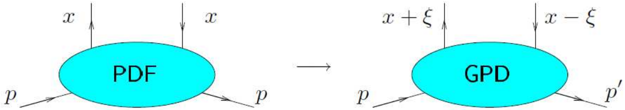
Transversity of the nucleon using hard processes

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.

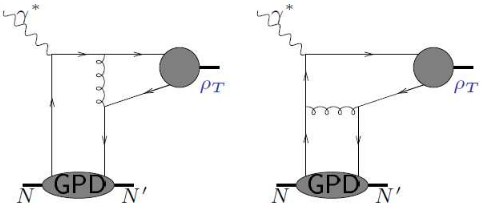


- For massless (anti)particles, chirality = (-)helicity
- Transversity is thus a chiral-odd quantity
- Since (in the massless limit) QCD and QED are chiral-even (γ^μ, $\gamma^\mu\gamma^5$), the chiral-odd quantities (1, γ^5, $[\gamma^\mu, \gamma^\nu]$) which one wants to measure should appear in pairs

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]

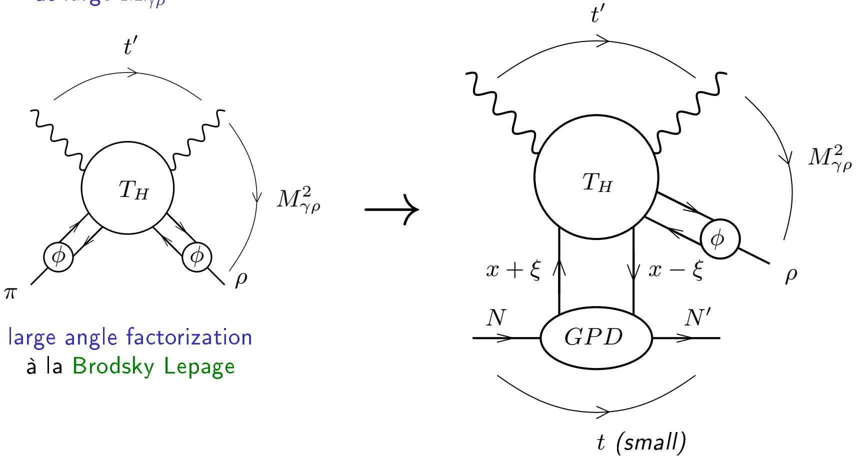
Transversity of the nucleon using hard processes: using a two body final state process?

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, 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.]

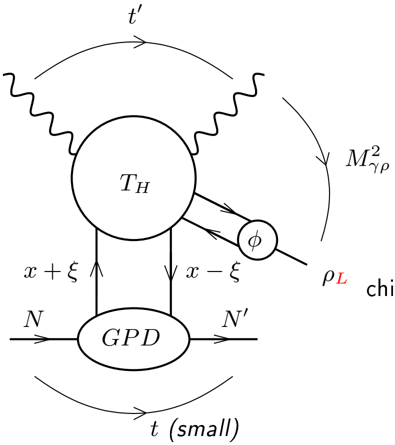
Probing GPDs using ρ meson + photon production

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



Probing chiral-even GPDs using ρ meson + photon production

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

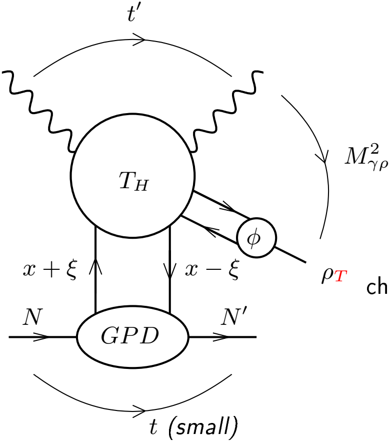


chiral-even twist 2 DA

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



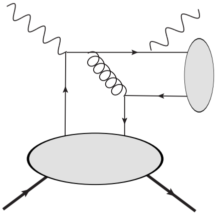
chiral-odd twist 2 DA

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?



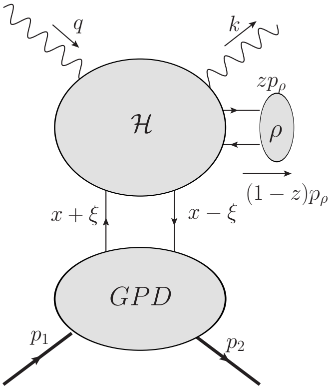
Typical non-zero diagram for a transverse ρ meson

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

Master formula based on leading twist 2 factorization

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

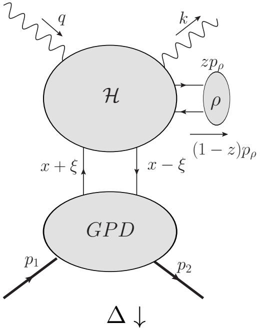
- Both the DA and the GPD can be either chiral-even or chiral-odd.
- At twist 2 the longitudinal ρ DA is chiral-even and the transverse ρ DA is chiral-odd.
- Hence we will need both chiral-even and chiral-odd non-perturbative building blocks and hard parts.



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:



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

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 and 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:

$$\phi_{||}(z) = 6z(1-z)\,,$$

$$\phi_{\perp}(z) = 6z(1-z)\,.$$

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

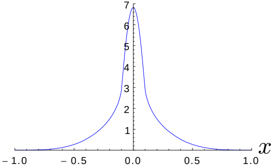
- $q(x)$: unpolarized PDF [GRV-98]
- $\Delta q(x)$ polarized PDF [GRSV-2000]
- $\delta q(x)$: transversity PDF [Anselmino *et al.*]

Model for GPDs: based on the Double Distribution ansatz

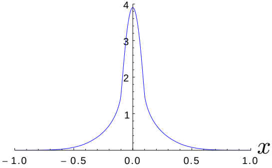
Typical sets of chiral-even GPDs

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

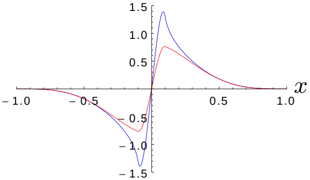
$H^u(x,\xi)$



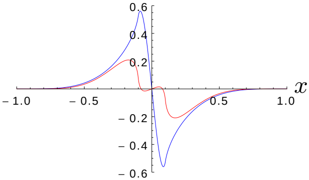
$H^d(x,\xi)$



$\tilde{H}^u(x,\xi)$



$\tilde{H}^d(x,\xi)$

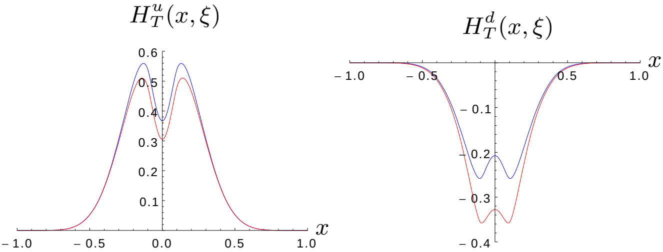


"valence" and "standard": two GRSV Ansätze for $\Delta q(x)$

Model for GPDs: based on the Double Distribution ansatz

Typical sets of chiral-odd GPDs

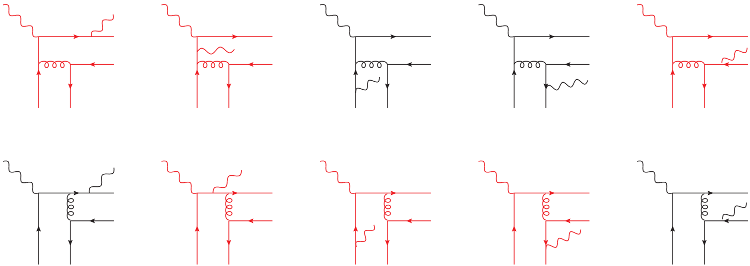
$$\xi = .1 \leftrightarrow S_{\gamma N} = 20 \text{ GeV}^2 \text{ and } M^2_{\gamma\rho} = 3.5 \text{ GeV}^2$$



"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
Red diagrams cancel in the chiral-odd case

Final computation

Final computation

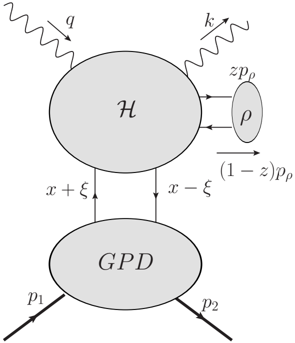
$$\mathcal{A} \propto \int_{-1}^{1} dx \int_{0}^{1} dz\; T(x,\xi,z)\; H(x,\xi,t)\; \Phi_\rho(z)$$

- 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

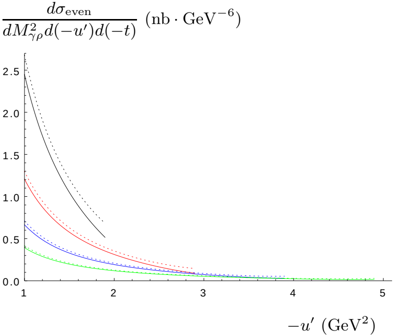
- Kinematical parameters: $S^2_{\gamma N}$, $M^2_{\gamma\rho}$ and $-u'$



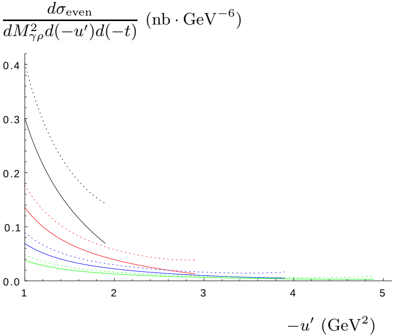
Fully differential cross section

Chiral even cross section

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



proton



neutron

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

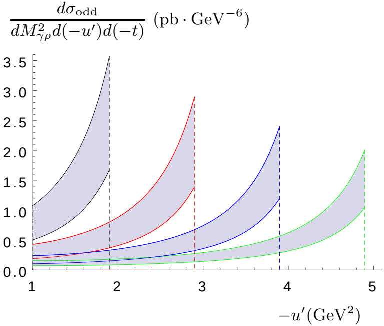
solid: “valence” model

dotted: “standard” model

Fully differential cross section

Chiral odd cross section

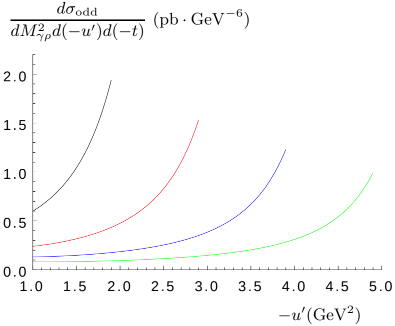
at $-t = (-t)_{\min}$



proton

"valence" and "standard" models,

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



neutron

"valence" model only

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

Phase space integration

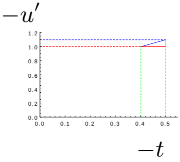
Evolution of the phase space in $(-t, -u')$ plane

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

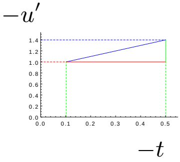
in practice: $-u' > 1\ \mathrm{GeV}^2$ and $-t' > 1\ \mathrm{GeV}^2$ and $(-t)_{\min} \leqslant -t \leqslant .5\ \mathrm{GeV}^2$

this ensures large $M^2_{\gamma\rho}$

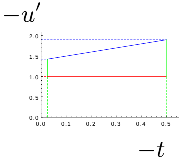
example: $S_{\gamma N} = 20\ \mathrm{GeV}^2$



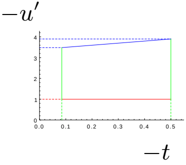
$M_{\gamma\rho} = 2.2\ \mathrm{GeV}^2$



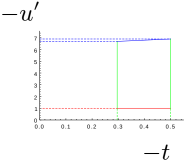
$M^2_{\gamma\rho} = 2.5\ \mathrm{GeV}^2$



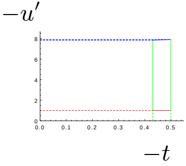
$M_{\gamma\rho} = 3\ \mathrm{GeV}^2$



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



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



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

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:

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

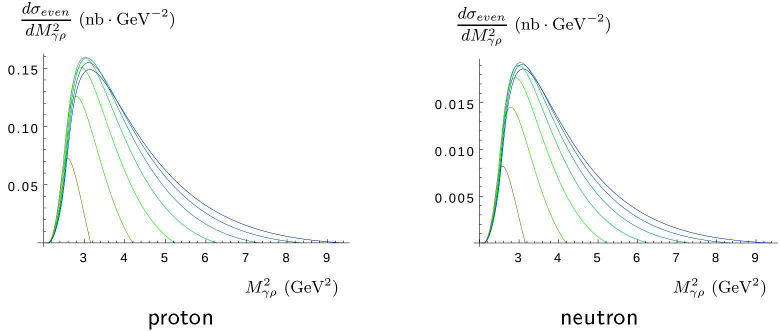
From the grid in $-u'$, the new grid in $-\tilde{u}'$ is given by just keeping the same α's:

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

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

Single differential cross section

Chiral even cross section

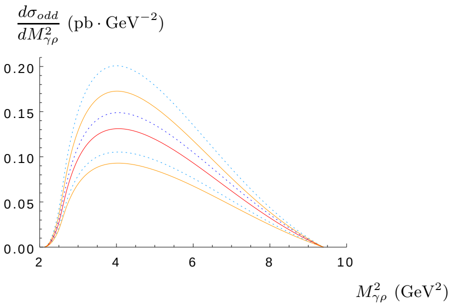


"valence" scenario

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

Single differential cross section

Chiral odd cross section



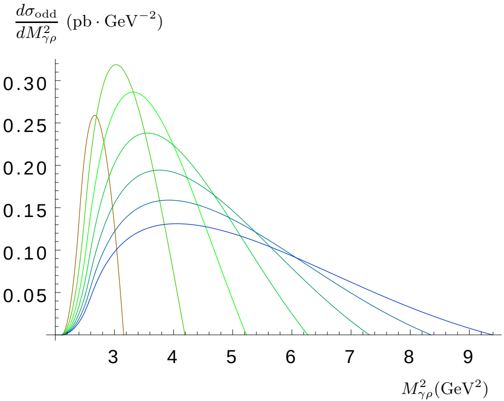
$$S_{\gamma N} = 20\text{GeV}^2$$

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

Chiral odd cross section

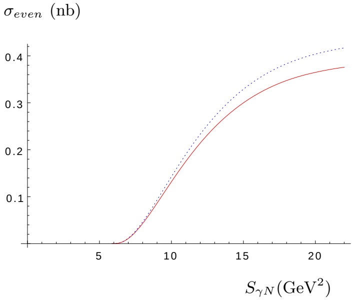


proton, "valence" scenario

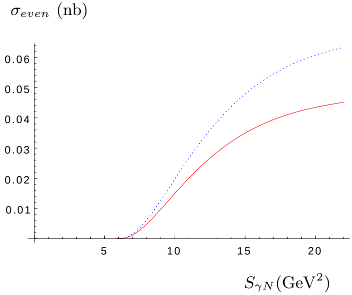
$S_{\gamma N}$ vary in the set 8, 10, 12, 14, 16, 18, 20 GeV^2 (from left to right)

Integrated cross-section

Chiral even cross section



proton

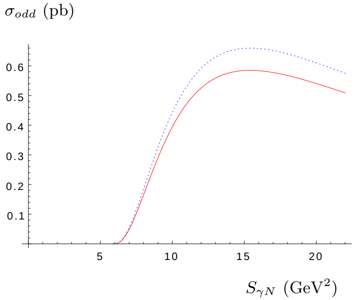


neutron

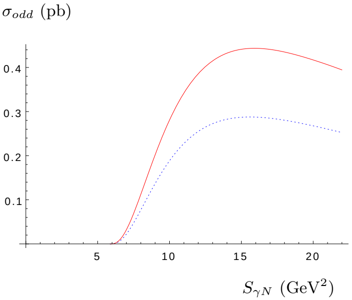
solid red: “valence” scenario
dashed blue: “standard” one

Integrated cross-section

Chiral odd cross section



proton



neutron

solid red: "valence" scenario

dashed blue: "standard" one

Counting rates for 100 days

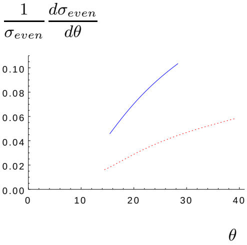
example: JLab Hall B

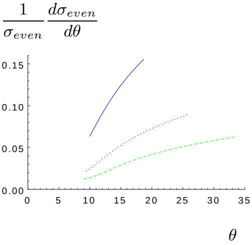
- untagged incoming $\gamma \Rightarrow$ Weizsäcker-Williams distribution
- With an expected luminosity of $\mathcal{L} = 100\ \mathrm{nb}^{-1}s^{-1}$, for 100 days of run:
  - Chiral even case : $\simeq 3\ 10^6\ \rho_L$.
  - Chiral odd case : $\simeq 7\ 10^3\ \rho_T$

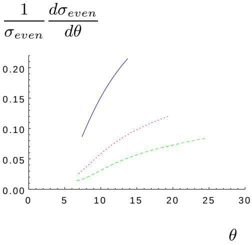
Effects of an experimental angular restriction for the produced γ?

Angular distribution of the produced γ (chiral-even cross section)

after boosting to the lab frame







$S_{\gamma N} = 10$ GeV^2	$S_{\gamma N} = 15$ GeV^2	$S_{\gamma N} = 20$ GeV^2
$M^2_{\gamma\rho} = 3, 4$ GeV^2	$M^2_{\gamma\rho} = 3, 4, 5$ GeV^2	$M^2_{\gamma\rho} = 3, 4, 5$ GeV^2

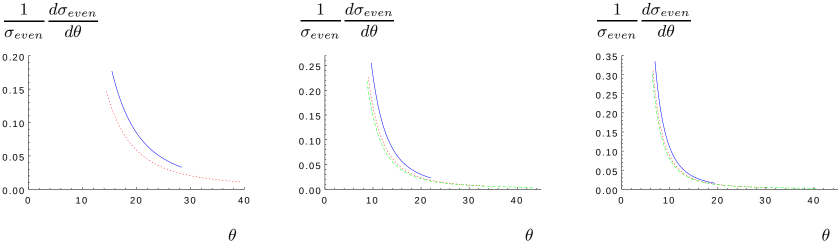
JLab Hall B detector equipped between 5° and 35°

$\Rightarrow$ this is safe!

Effects of an experimental angular restriction for the produced γ?

Angular distribution of the produced γ (chiral-odd cross section)

after boosting to the lab frame



$S_{\gamma N} = 10 \text{ GeV}^2$	$S_{\gamma N} = 15 \text{ GeV}^2$	$S_{\gamma N} = 20 \text{ GeV}^2$
$M^2_{\gamma\rho} = 3, 4 \text{ GeV}^2$	$M^2_{\gamma\rho} = 3.5, 5, 6.5 \text{ GeV}^2$	$M^2_{\gamma\rho} = 4, 6, 8 \text{ GeV}^2$

JLab Hall B detector equipped between 5° and 35°

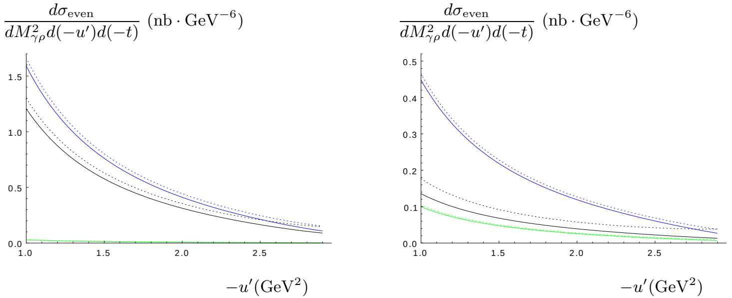
$\Rightarrow$ this is safe!

Conclusion

- High statistics for the chiral-even component: enough to extract H ($\tilde{H}$?) and test the universality of GPDs
- In this chiral-even sector: analogy with Timelike Compton Scattering, the $\gamma\rho$ pair playing the role of the γ^*.
- Strong dominance of the chiral-even component w.r.t. the chiral-odd one:
  - In principle the separation ρ_L/ρ_T can be performed by an angular analysis of its decay products, but this could be very challenging.
    Cuts in θ_γ might help
  - Future: study of polarization observables $\Rightarrow$ sensitive to the interference of these two amplitudes
- The Bethe Heitler component (outgoing γ emitted from the incoming lepton) is:
  - zero for the chiral-odd case
  - suppressed for the chiral-even case
- Our result can also be applied to electroproduction ($Q^2 \neq 0$) after adding Bethe-Heitler contributions and interferences.
- Possible measurement at JLAB (Hall B, C, D)
- A similar study could be performed at COMPASS, EIC, LHC in UPC?

Chiral-even cross section

Contribution of u versus d



proton neutron

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

$u + d$ quarks u quark d quark

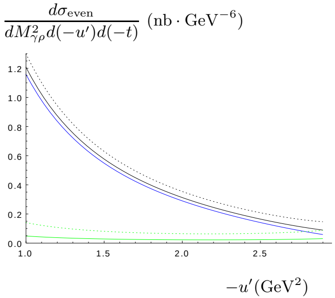
Solid: “valence” model

dotted: “standard” model

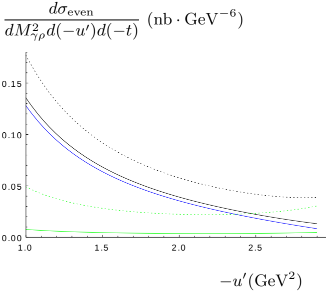
- u-quark contribution dominates due to the charge effect
- the interference between u and d contributions is important and negative.

Chiral-even cross section

Contribution of vector versus axial amplitudes



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