Accessing GPDs through the exclusive photoproduction of a γ-meson pair with large invariant mass

Assemblée Générale du GdR QCD

Saad Nabeebaccus

saad.nabeebaccus@ijclab.in2p3.fr

May 24, 2022

With S. Wallon, L. Szymanowski, B. Pire, R. Boussarie, G. Duplančić, K. Passek-Kumerički

DVCS: exclusive process (non forward amplitude)

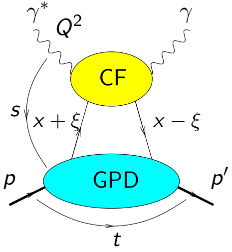
(DVCS: Deep Vitual Compton Scattering)

Fourier transf.: $t \leftrightarrow$ impact parameter

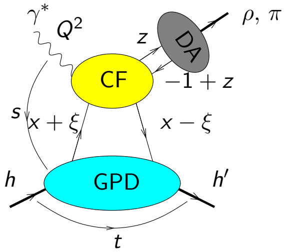
$(x,\ t) \Rightarrow$ 3-dimensional structure

Coefficient Function (hard) $\otimes$ Generalized Parton Distribution (soft)

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



Meson production: γ replaced by $\rho,\ \pi, \cdots$



GPD (soft) $\otimes$ CF (hard) $\otimes$ Distribution Amplitude (soft)

Collins, Frankfurt, Strikman '97; Radyushkin '97

proofs valid only for some restricted cases

Quark GPDs at twist 2

without helicity flip (chiral-even Γ matrices): 4 chiral-even GPDs:
(Note: $\Delta = p' - p$)

$$F^q = \frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-}\, \langle p'|\, \bar{q}(-\tfrac{1}{2}z)\,\gamma^+ q(\tfrac{1}{2}z)\,|p\rangle\Big|_{z^+=0,\, z_\perp=0}$$

$$= \frac{1}{2P^+}\left[H^q(x,\xi,t)\,\bar{u}(p')\gamma^+ u(p) + E^q(x,\xi,t)\,\bar{u}(p')\frac{i\,\sigma^{+\alpha}\Delta_\alpha}{2m}u(p)\right],$$

Quark GPDs at twist 2

without helicity flip (chiral-even Γ matrices): 4 chiral-even GPDs:
(Note: $\Delta = p' - p$)

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

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

Quark GPDs at twist 2

without helicity flip (chiral-even Γ matrices): 4 chiral-even GPDs:
(Note: $\Delta = p' - p$)

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

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

$H^q \xrightarrow{\xi=0,t=0}$ PDF q $\qquad$ $\tilde{H}^q \xrightarrow{\xi=0,t=0}$ polarized PDF Δq

with helicity flip (chiral-odd Γ matrices): 4 chiral-odd GPDs:

$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-}\,\langle p'|\,\bar{q}(-\tfrac{1}{2}z)\; i\,\sigma^{+i}\; q(\tfrac{1}{2}z)\;|p\rangle\Big|_{z^+=0,\,z_\perp=0}$$

$$= \frac{1}{2P^+}\bar{u}(p')\Big[H_T^q\, i\sigma^{+i} + \tilde{H}_T^q\,\frac{P^+\Delta^i - \Delta^+P^i}{m^2}$$

$$+E_T^q\,\frac{\gamma^+\Delta^i - \Delta^+\gamma^i}{2m} + \tilde{E}_T^q\,\frac{\gamma^+P^i - P^+\gamma^i}{m}\Big]\,u(p)\,,$$

with helicity flip (chiral-odd Γ matrices): 4 chiral-odd GPDs:

$$\frac{1}{2}\int \frac{dz^-}{2\pi}\, e^{ixP^+z^-}\langle p'|\, \bar{q}(-\tfrac{1}{2}z)\, i\,\sigma^{+i}\, q(\tfrac{1}{2}z)\ |p\rangle\Big|_{z^+=0,\, z_\perp=0}$$

$$= \frac{1}{2P^+}\bar{u}(p')\left[H_T^q\, i\sigma^{+i} + \tilde{H}_T^q\,\frac{P^+\Delta^i - \Delta^+P^i}{m^2} + E_T^q\,\frac{\gamma^+\Delta^i - \Delta^+\gamma^i}{2m} + \tilde{E}_T^q\,\frac{\gamma^+P^i - P^+\gamma^i}{m}\right]u(p)\,,$$

$$H_T^q \xrightarrow{\xi=0,t=0} \text{quark transversity PDFs } \delta q$$

Note: $\tilde{E}_T^q(x,-\xi,t) = -\tilde{E}_T^q(x,\xi,t)$

Why consider a gamma-meson pair?
Understanding 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 PDFs. Poorly known.

Why consider a gamma-meson pair?
Understanding 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 PDFs. Poorly known.
- Transversity GPDs are completely unknown experimentally.
- For massless (anti)particles, chirality = (-)helicity
- Transversity GPDs can thus be accessed through chiral-odd Γ matrices.

Why consider a gamma-meson pair?
Understanding 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 PDFs. Poorly known.

- Transversity GPDs are completely unknown experimentally.
- For massless (anti)particles, chirality = (-)helicity
- Transversity GPDs can thus be accessed through chiral-odd Γ matrices.
- 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.

Why consider a gamma-meson pair?

Can we probe transversity GPDs in meson production?

- the leading DA of ρ_T is of twist 2 and chiral-odd ($\sigma^{\mu\nu}$ coupling)

Why consider a gamma-meson pair?

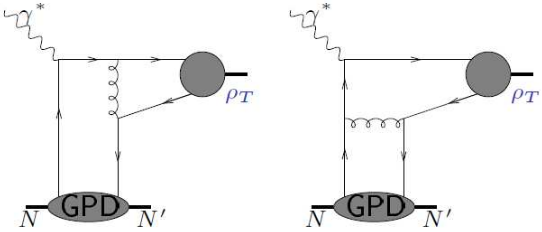
Can we probe transversity GPDs in meson production?

- the leading DA of ρ_T is of twist 2 and chiral-odd ($\sigma^{\mu\nu}$ coupling)
- unfortunately $\gamma^* N^\uparrow \to \rho_T N' = 0$, since such a process would require a helicity transfer of 2 from a photon. [Diehl, Gousset, Pire], [Collins, Diehl]

Why consider a gamma-meson pair?

Can we probe transversity GPDs in meson production?

- the leading DA of ρ_T is of twist 2 and chiral-odd ($\sigma^{\mu\nu}$ coupling)
- unfortunately $\gamma^* N^\uparrow \to \rho_T N' = 0$, since such a process would require a helicity transfer of 2 from a photon. [Diehl, Gousset, Pire], [Collins, Diehl]
- lowest order diagrammatic argument:



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

Why consider a gamma-meson pair?

Go to higher twist?

- This vanishing only occurs at twist 2
- At twist 3 this process does not vanish [Ahmad, Goldstein, Liuti], [Goloskokov, Kroll]

Why consider a gamma-meson pair?
Go to higher twist?

- 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, Wallon]

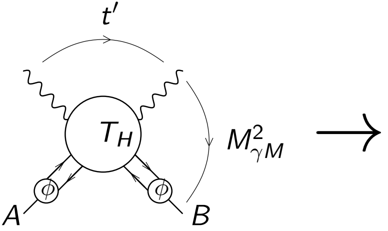
Why consider a gamma-meson pair?
A convenient alternative solution

- Circumvent this using 3-body final states [Ivanov, Pire, Szymanowski, Teryaev], [Enberg, Pire, Szymanowski], [El Beiyad, Pire, Segond, Szymanowski, Wallon]
- Consider the process $\gamma N \to \gamma M N'$, $M =$meson.

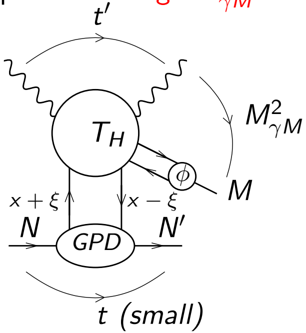
Why consider a gamma-meson pair?

A convenient alternative solution

- Circumvent this using 3-body final states [Ivanov, Pire, Szymanowski, Teryaev], [Enberg, Pire, Szymanowski], [El Beiyad, Pire, Segond, Szymanowski, Wallon]
- Consider the process $\gamma N \to \gamma M N'$, $M =$meson.
- Collinear factorisation of the amplitude at large $M^2_{\gamma M}$.

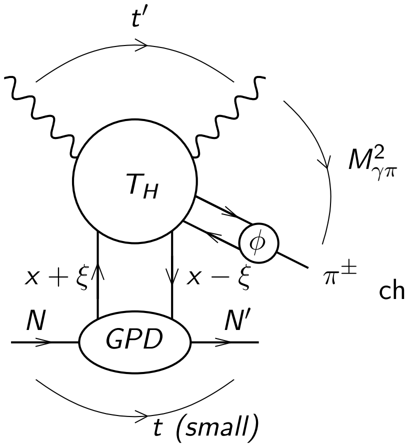


large angle factorization
à la Brodsky Lepage



Why consider a gamma-meson pair?

Chiral-even GPDs using $\pi^{\pm}\gamma$ production

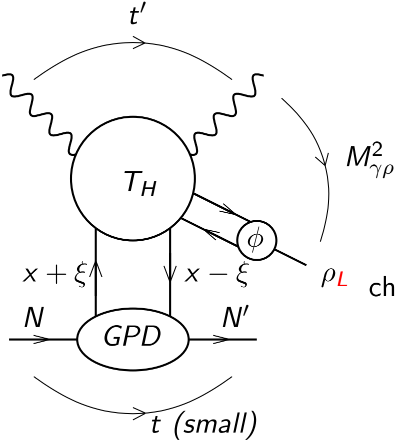


chiral-even twist 2 DA

chiral-even twist 2 GPD

[G. Duplančić, K. Passek-Kumerički, B. Pire, L. Szymanowski, S. Wallon]

Why consider a gamma-meson pair?
Chiral-even GPDs using $\rho_L \gamma$ production



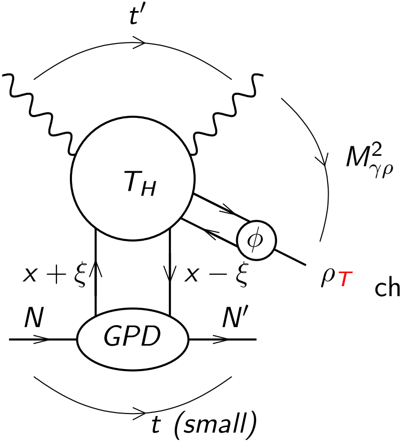
chiral-even twist 2 DA

chiral-even twist 2 GPD

[R. Boussarie, B. Pire, L. Szymanowski, S. Wallon]

Why consider a gamma-meson pair?

Chiral-odd GPDs using $\rho_T \gamma$ production

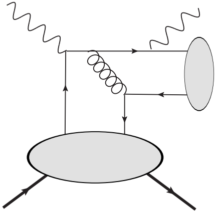


chiral-odd twist 2 DA

chiral-odd twist 2 GPD

[R. Boussarie, B. Pire, L. Szymanowski, S. Wallon]

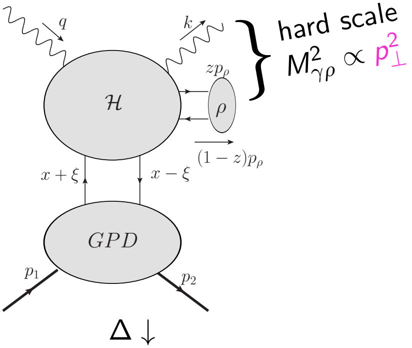
How does it work?



Typical non-zero diagram for a transverse ρ meson

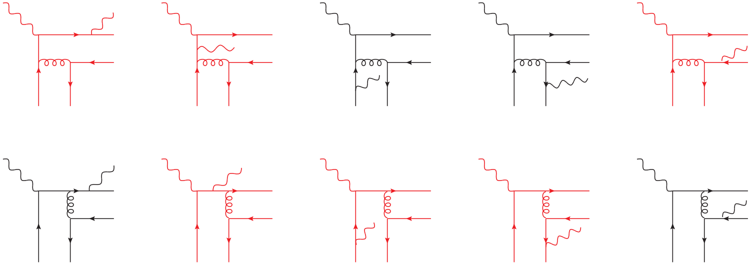
the σ matrices (from either the DA or the GPD) do not kill it anymore!

$$\gamma^{(*)}(q) + N(p_1) \to \gamma(k) + \rho^0(p_\rho, \varepsilon_\rho) + N'(p_2)$$



Useful Mandelstam variables: $t = (p_2 - p_1)^2$, $u' = (p_\rho - q)^2$

A total of 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

We parameterise the GPDs in terms of *double distributions (Radyushkin-type parametrisation)*

We parameterise the GPDs in terms of *double distributions (Radyushkin-type parametrisation)*

For polarized PDFs (and hence transversity PDFs), two scenarios are proposed for the parameterization:

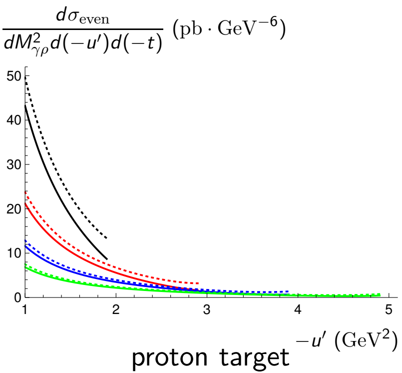
- "standard" scenario, with flavor-symmetric light sea quark and antiquark distributions.
- "valence" scenario with a completely flavor-asymmetric light sea quark densities.

- We take the simplistic asymptotic form of the DAs

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

- A non asymptotical wave function can be also investigated (preliminary):

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



$$S_{\gamma N} = 20 \text{ GeV}^2, \text{ at } -t = (-t)_{\min}$$

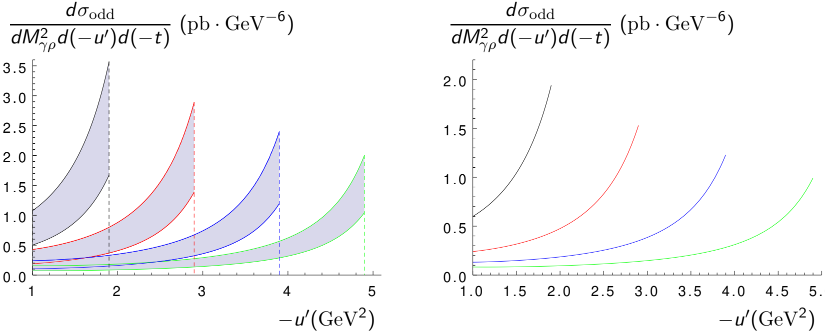
$$M^2_{\gamma\rho} = 3, 4, 5, 6 \text{ GeV}^2$$

dotted: "standard" model

solid: "valence" model

Results

Fully-differential cross-sections: ρ_T (Chiral odd)



proton target

"valence" and "standard" models,

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

neutron target

"valence" model only

$$S_{\gamma N} = 20\ \mathrm{GeV}^2 \text{ at } -t = (-t)_{\rm min}$$

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

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

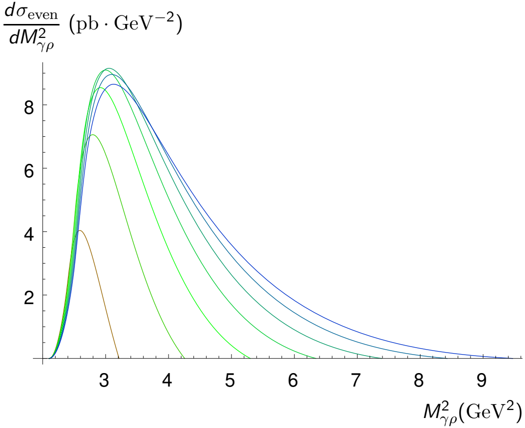
$\Longrightarrow$ $-u' > 1\ \mathrm{GeV}^2$ and $-t' > 1\ \mathrm{GeV}^2$ and $(-t)_{\mathrm{min}} \leqslant -t \leqslant .5\ \mathrm{GeV}^2$

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

$\Longrightarrow$ $-u' > 1 \text{ GeV}^2$ and $-t' > 1 \text{ GeV}^2$ and $(-t)_{\text{min}} \leqslant -t \leqslant .5 \text{ GeV}^2$

See backup slides for more details, including information on the phase space evolution in the $(-t, -u')$ plane.

Single differential cross-section: ρ_L (Chiral even)



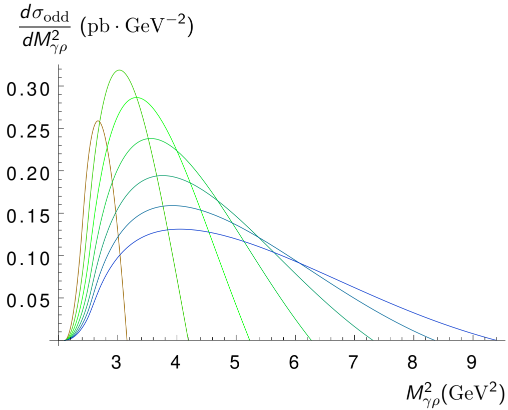
proton target, "valence" scenario

$$S_{\gamma N} = 8,\ 10,\ 12,\ 14,\ 16,\ 18,\ 20\ \text{GeV}^2$$

typical JLab kinematics

Results

Single differential cross-section: ρ_T (Chiral odd)

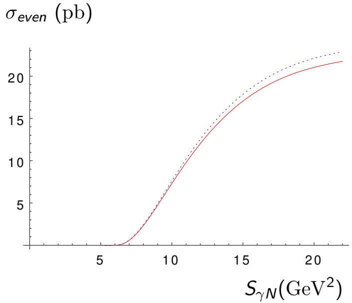


proton target, "valence" scenario

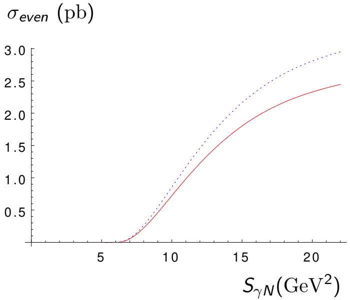
$S_{\gamma N}$ = 8, 10, 12, 14, 16, 18, 20 GeV^2

typical JLab kinematics

Integrated cross-section: Valence vs Standard: ρ_L (Chiral even)



proton target



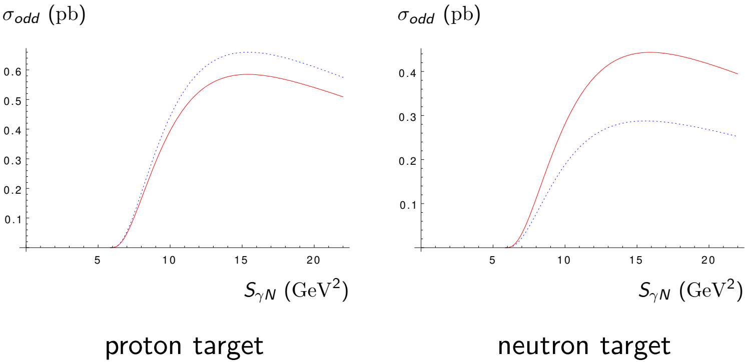
neutron target

solid red: "valence" scenario

dashed blue: "standard" one

Results

Integrated cross-section: Valence vs Standard: ρ_T (Chiral odd)

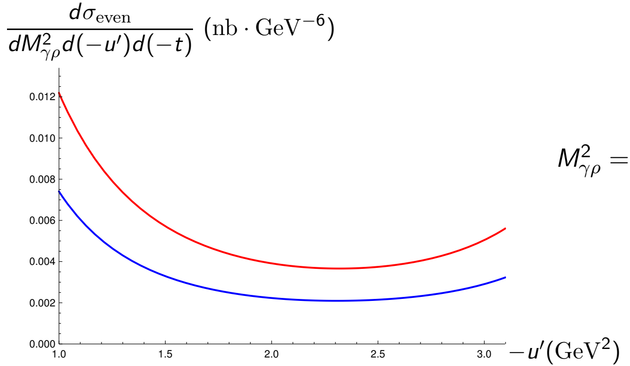


solid red: "valence" scenario

dashed blue: "standard" one

comparing singular DA ($\propto \sqrt{z(1-z)}$)
vs asymptotical DA ($\propto z(1-z)$).

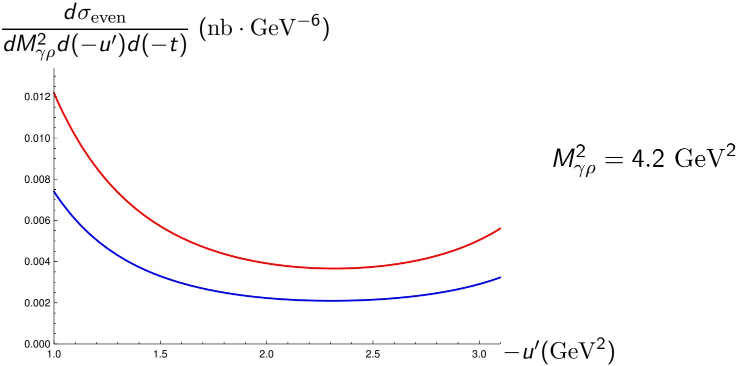
"valence" model for the polarized PDFs



$M^2_{\gamma\rho} = 4.2 \text{ GeV}^2$

comparing singular DA ($\propto \sqrt{z(1-z)}$)
vs asymptotical DA ($\propto z(1-z)$).

"valence" model for the polarized PDFs



$\Longrightarrow$ sizable effect, larger than the one due to uncertainties on polarized PDFs

Good statistics: For example, at JLab Hall B:

- untagged incoming $\gamma \Rightarrow$ Weizsäcker-Williams distribution

Good statistics: For example, at 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:
  - $\rho_L^0 : \approx 7.6 \times 10^4$ (Chiral-even)
  - $\rho_T^0 : \approx 7.5 \times 10^3$ (Chiral-odd)
  - $\pi^+ : \approx 5.8 \times 10^4$ (Chiral-even)
  - $\pi^- : \approx 4.1 \times 10^4$ (Chiral-even)

Prospects at experiments

EIC, LHC at UPC,...

- Need to adjust kinematics for searches at EIC, LHC in ultra-peripheral collisions (UPC), LHeC and COMPASS.

- Need to adjust kinematics for searches at EIC, LHC in ultra-peripheral collisions (UPC), LHeC and COMPASS.

Preliminary results (Chiral-even) for ultra-peripheral p-Pb collisions at LHC (ATLAS and CMS):

- With future data from runs 3 and 4,
  - $\rho_L^0 : \approx 4.9 \times 10^3$
  - $\pi^+ : \approx 2.7 \times 10^3$
  - $\pi^- : \approx 1.9 \times 10^3$

- Need to adjust kinematics for searches at EIC, LHC in ultra-peripheral collisions (UPC), LHeC and COMPASS.

Preliminary results (Chiral-even) for ultra-peripheral p-Pb collisions at LHC (ATLAS and CMS):

- With future data from runs 3 and 4,
  - $\rho_L^0 : \approx 4.9 \times 10^3$
  - $\pi^+ : \approx 2.7 \times 10^3$
  - $\pi^- : \approx 1.9 \times 10^3$
- For data already taken, about 1 order of magnitude less...
  $\Longrightarrow$ *Low luminosity not being compensated by larger photon flux.*

Outlook

- Use non-asymptotical DA, $\phi_M(z) = \frac{8}{\pi}\sqrt{z(1-z)}$, (instead of $\phi_M(z) = 6z(1-z)$) to model the outgoing meson M: suggested by AdS/QCD correspondence, dynamical chiral symmetry breaking. [Ongoing]

Outlook

- Use non-asymptotical DA, $\phi_M(z) = \frac{8}{\pi}\sqrt{z(1-z)}$, (instead of $\phi_M(z) = 6z(1-z)$) to model the outgoing meson M: suggested by AdS/QCD correspondence, dynamical chiral symmetry breaking. [Ongoing]
- Investigate polarisation asymmetries of the initial γ. [Ongoing]

Outlook

- Use non-asymptotical DA, $\phi_M(z) = \frac{8}{\pi}\sqrt{z(1-z)}$, (instead of $\phi_M(z) = 6z(1-z)$) to model the outgoing meson M: suggested by AdS/QCD correspondence, dynamical chiral symmetry breaking. [Ongoing]
- Investigate polarisation asymmetries of the initial γ. [Ongoing]
- Adjust kinematics for searches at EIC, LHC at UPC, LHeC and COMPASS. [Ongoing]

Outlook

- Use non-asymptotical DA, $\phi_M(z) = \frac{8}{\pi}\sqrt{z(1-z)}$, (instead of $\phi_M(z) = 6z(1-z)$) to model the outgoing meson M: suggested by AdS/QCD correspondence, dynamical chiral symmetry breaking. [Ongoing]
- Investigate polarisation asymmetries of the initial γ. [Ongoing]
- Adjust kinematics for searches at EIC, LHC at UPC, LHeC and COMPASS. [Ongoing]
- Add Bethe-Heitler component (photon emitted from incoming lepton)
  - zero in chiral-odd case.
  - suppressed in chiral-even case, but could estimate their contributions.

Outlook

- Compute NLO corrections.
  - Cancellation of IR divergences: Indication that QCD factorisation works.

Outlook

- Compute NLO corrections.
  - Cancellation of IR divergences: Indication that QCD factorisation works.
- The processes $\gamma N \to \gamma \pi^0 N'$ and $\gamma N \to \gamma \eta^0 N'$ are of particular interest, since they give access to gluonic GPDs at Born level.

Outlook

- Compute NLO corrections.
  - Cancellation of IR divergences: Indication that QCD factorisation works.
- The processes $\gamma N \to \gamma \pi^0 N'$ and $\gamma N \to \gamma \eta^0 N'$ are of particular interest, since they give access to gluonic GPDs at Born level.
- Consider twist-3 contributions.

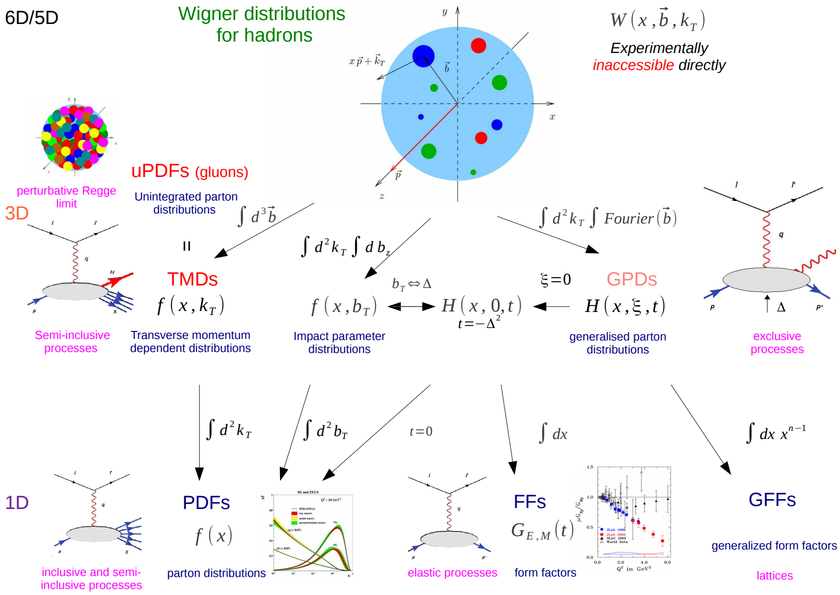
Outlook

- Compute NLO corrections.
  - Cancellation of IR divergences: Indication that QCD factorisation works.
- The processes $\gamma N \to \gamma \pi^0 N'$ and $\gamma N \to \gamma \eta^0 N'$ are of particular interest, since they give access to gluonic GPDs at Born level.
- Consider twist-3 contributions.
- Generalise to electroproduction ($Q^2 \neq 0$) (and include Bethe-Heitler contributions).

The END

BACKUP SLIDES

What are GPDs?
From Wigner distributions to GPDs and PDFs



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

$$\int \frac{dz^-}{4\pi} e^{ixP^+z^-} \langle p_2, \lambda_2 | \bar{\psi}_q \left(-\frac{1}{2}z^-\right) \gamma^+\gamma^5 \psi \left(\frac{1}{2}z^-\right) | p_1, \lambda_1 \rangle$$
$$= \frac{1}{2P^+} \bar{u}(p_2, \lambda_2) \left[\tilde{H}^q(x, \xi, t)\gamma^+\gamma^5 + \tilde{E}^q(x, \xi, t) \frac{\gamma^5\Delta^+}{2m} \right] u(p_1, \lambda_1)$$

- Take the limit $\Delta_\perp = 0$.
- In that case and for small ξ, the dominant contributions come from H^q and $\tilde{H}^q$.

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

- Take the limit $\Delta_\perp = 0$.
- In that case and for small ξ, the dominant contributions come from H_T^q.

- GPDs can be represented in terms of Double Distributions [Radyushkin]

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

- GPDs can be represented in terms of Double Distributions [Radyushkin]

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

- 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:

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

- GPDs can be represented in terms of Double Distributions [Radyushkin]

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

- 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:

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

  - $\Pi(\beta,\alpha) = \frac{3}{4}\frac{(1-\beta)^2-\alpha^2}{(1-\beta)^3}$: 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 ($C = 0.71\mathrm{GeV}^2$)

Sets of used PDFs

- $q(x)$: unpolarized PDF [GRV-98]

  and [MSTW2008lo, MSTW2008nnlo, ABM11nnlo, CT10nnlo]

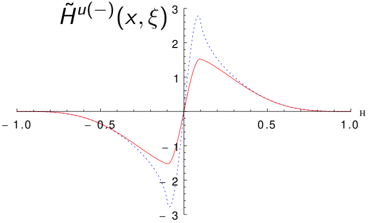
- $\Delta q(x)$ polarized PDF [GRSV-2000]

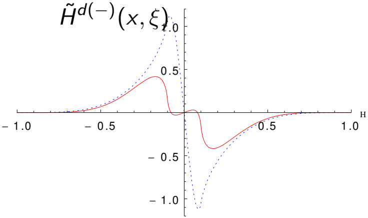
- $\delta q(x)$: transversity PDF [Anselmino *et al.*]

Effects are not significant! But relevant for NLO corrections!

Typical kinematic point: $\xi = .1 \leftrightarrow S_{\gamma N} = 20\ \mathrm{GeV}^2$ and $M^2_{\gamma\rho} = 3.5\ \mathrm{GeV}^2$

$$\tilde{H}^{q(-)}(x,\xi,t) = \tilde{H}^q(x,\xi,t) - \tilde{H}^q(-x,\xi,t) \quad [C = -1]$$





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

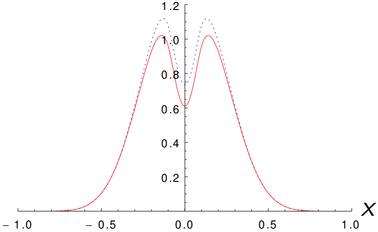
Computation

Valence vs Standard scenarios in H_T (Chiral-odd)

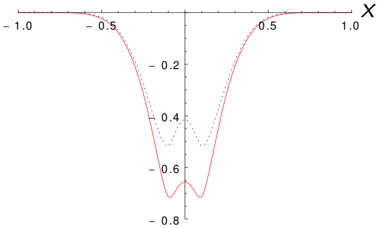
Typical Kinematic Point: $\xi = .1 \leftrightarrow S_{\gamma N} = 20 \ \mathrm{GeV}^2$ and $M^2_{\gamma\rho} = 3.5 \ \mathrm{GeV}^2$

$$H_T^{q(-)}(x,\xi,t) = H_T^q(x,\xi,t) + H_T^q(-x,\xi,t) \quad [C = -1]$$

$H_T^{u(-)}(x,\xi)$



$H_T^{d(-)}(x,\xi)$



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

$\Rightarrow$ two Ansätze for $\delta q(x)$

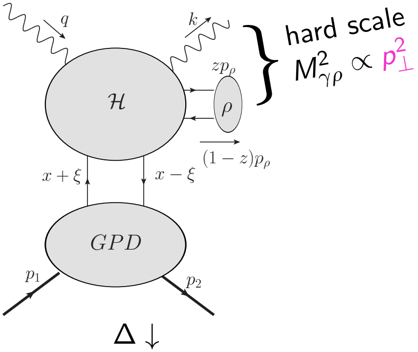
- Helicity conserving (vector) DA at twist 2: ρ_L

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

- ρ_T DA at twist 2:

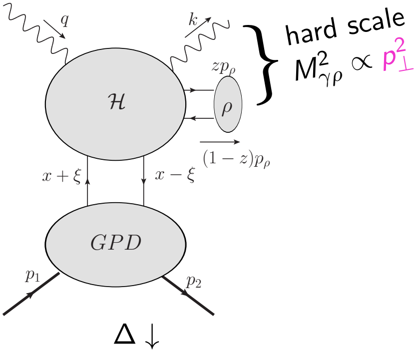
$$\langle 0|\bar{u}(0)\sigma^{\mu\nu} u(x)|\rho^0(p,s)\rangle = \frac{i}{\sqrt{2}} (\epsilon_\rho^\mu p^\nu - \epsilon_\rho^\nu p^\mu) f_\rho^\perp \int_0^1 du\ e^{-iup\cdot x}\ \phi_\perp(u)$$

- Work in the limit of:
  - $\Delta_\perp \ll p_\perp$
  - $M^2, \ m_\rho^2 \ll M_{\gamma\rho}^2$



- Work in the limit of:
  - $\Delta_\perp \ll p_\perp$
  - $M^2,\ m_\rho^2 \ll M_{\gamma\rho}^2$
- initial state particle momenta:

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



- Work in the limit of:
  - $\Delta_\perp \ll p_\perp$
  - $M^2,\ m_\rho^2 \ll M_{\gamma\rho}^2$
- initial state particle momenta:

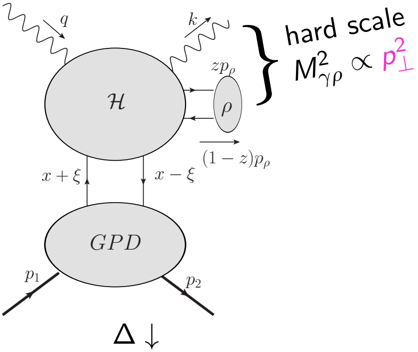
$$q^\mu = n^\mu,$$
$$p_1^\mu = (1+\xi)\, p^\mu + \frac{M^2}{s(1+\xi)} n^\mu$$

- final state particle momenta:

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

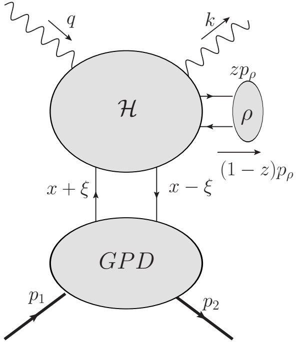
$$k^\mu = \alpha\, n^\mu + \frac{(\vec{p}_t - \vec{\Delta}_t/2)^2}{\alpha s} p^\mu + p_\perp^\mu - \frac{\Delta_\perp^\mu}{2}\ ,$$

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



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

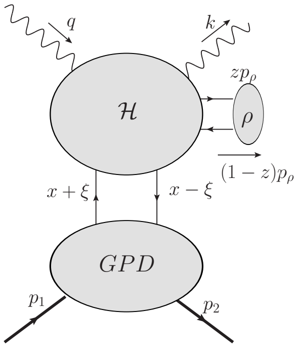
- z integration performed analytically using an asymptotic DA $\propto z(1-z)$
- GPD models plugged into expression for amplitude and the integral performed w.r.t. x numerically.



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

- z integration performed analytically using an asymptotic DA $\propto z(1-z)$
- GPD models plugged into expression for amplitude and the integral performed w.r.t. x numerically.
- Differential cross section:

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



- Kinematic parameters: $S_{\gamma N}$, $M^2_{\gamma\rho}$ and $-u'$
  Recall: $u' = (p_\rho - q)^2$, $t = (p_2 - p_1)^2$

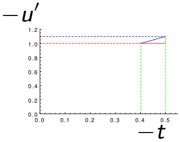
large angle scattering: $M^2_{\gamma\rho} \sim -u' \sim -t'$

$\Longrightarrow$ $-u' > 1 \text{ GeV}^2$ and $-t' > 1 \text{ GeV}^2$ and $(-t)_{\min} \leqslant -t \leqslant .5 \text{ GeV}^2$

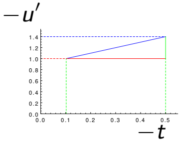
large angle scattering: $M^2_{\gamma\rho} \sim -u' \sim -t'$

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

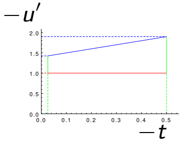
example: $S_{\gamma N} = 20\ \mathrm{GeV}^2$



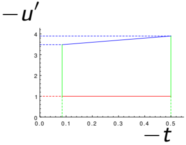
$M_{\gamma\rho} = 2.2\ \mathrm{GeV}^2$



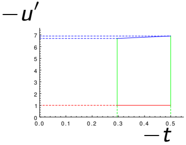
$M^2_{\gamma\rho} = 2.5\ \mathrm{GeV}^2$



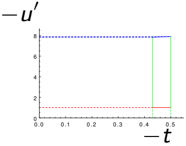
$M_{\gamma\rho} = 3\ \mathrm{GeV}^2$



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

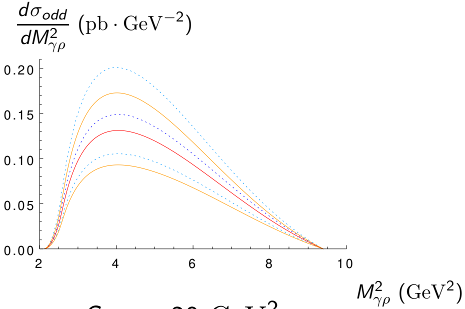


$M_{\gamma\rho} = 8\ \mathrm{GeV}^2$



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

Single differential cross-section: Valence vs Standard: ρ_T (Chiral odd)



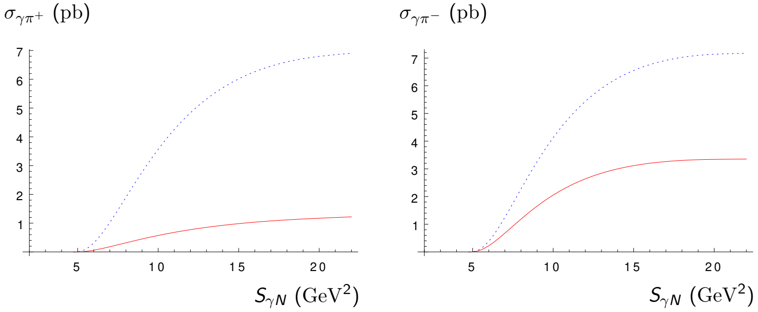
$$S_{\gamma N} = 20 \text{ GeV}^2$$

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 $\pm 2\sigma$.

Results

Integrated cross-section: Valence vs Standard: $\pi^{\pm}$ (Chiral even)



proton target | neutron target

solid red: "valence" scenario

dashed blue: "standard" one