Accessing Generalized Parton Distributions through $2 \to 3$ exclusive processes

Samuel Wallon

Laboratoire de Physique des 2 Infinis Irène Joliot-Curie
IJCLab
CNRS / Université Paris Saclay
Orsay

InterUniversity Institute for High Energies

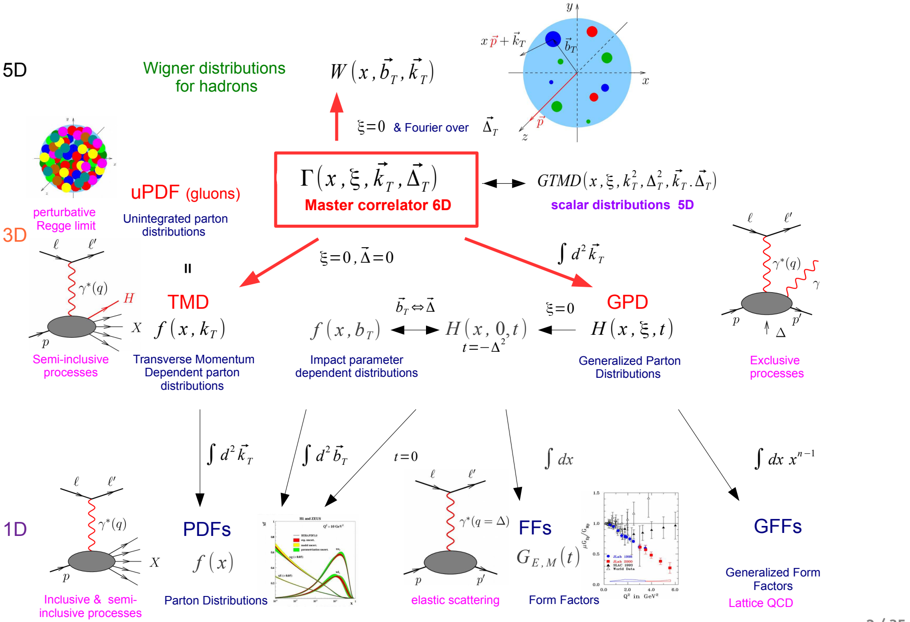
12th February 2025

Brussels

in collaboration with:

R. Boussarie (CPHT, Palaiseau), M. El Beyiad,
S. Nabeebaccus (Manchester U.) D. Perez (IJCLab) B. Pire (CPhT, Palaiseau),
J. Schoenleber (RIKEN, BNL) L. Szymanowski (NCBJ, Warsaw),
G. Duplančić, K. Passek-Kumerički (IRB, Zagreb)

The big picture



Extensions from DIS

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

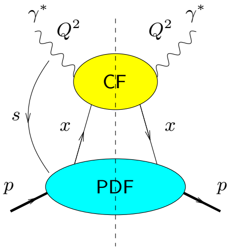
  (DIS: Deep Inelastic Scattering)

  ex: $e^{\pm} p \to e^{\pm} X$ at HERA

  $x \Rightarrow$ 1-dimensional structure

  Structure Function

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



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

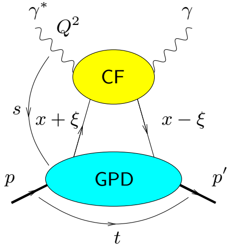
  (DVCS: Deep Vitual Compton Scattering)

  Fourier transf.: $t \leftrightarrow$ impact parameter

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

  Amplitude

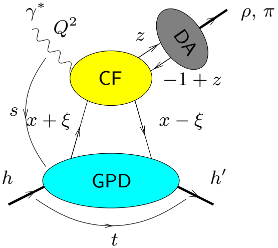
  $=$ Coefficient Function (hard) $\otimes$ Generalized Parton Distribution (soft)



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

Extensions from DVCS

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



Amplitude

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

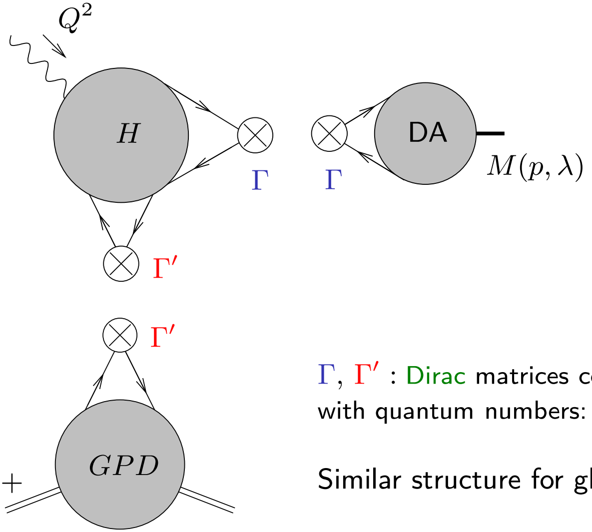
Collins, Frankfurt, Strikman '97; Radyushkin '97

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

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

  - with helicity flip (chiral-odd Γ' mat.): 4 chiral-odd GPDs:
    $H_T^q \xrightarrow{\xi=0,t=0}$ quark transversity PDFs δq, E_T^q, $\tilde{H}_T^q$, $\tilde{E}_T^q$

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

Collinear factorization

Twist 2 GPDs

Classification of twist 2 GPDs

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

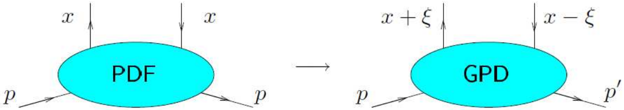
Chiral-odd sector: Transversity of the nucleon using hard processes

What is transversity?

- Transverse spin content of the proton:

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

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

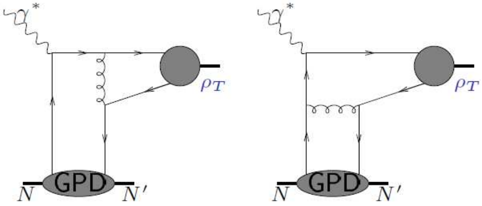


- For massless (anti)particles, chirality = (-)helicity
- Transversity is thus a chiral-odd quantity
- Since (in the massless limit) QCD and QED are chiral-even $(\gamma^\mu,\ \gamma^\mu\gamma^5)$, the chiral-odd quantities $(1,\ \gamma^5,\ [\gamma^\mu, \gamma^\nu])$ which one wants to measure should 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 $\gamma^* N^\uparrow \to \rho_T N' = 0$
  - 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?

Go to higher twist?

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.]

Transversity of the nucleon using hard processes: using a 3-body final state

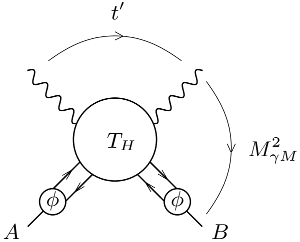
3-body final state process

- $\gamma N \to M M N'$:
  - at small-x:
    D. Ivanov, B. Pire, L. Szymanowski, O. Teryaev [hep-ph/0209300]
    R. Enberg, B. Pire, L. Szymanowski [hep-ph/0601138]
  - at medium energies (GPDs):
    M. El Beiyad, B. Pire, M. Segond, L. Szymanowski, SW [1001.4491]
- $\gamma N \to \gamma M N'$:
  R. Boussarie, B. Pire, L. Szymanowski, SW [1609.03830]
  G. Duplančić, K. Passek-Kumerički, B. Pire, L. Szymanowski, SW [1809.08104]
  G. Duplančić, S. Nabeebaccus, K. Passek-Kumerički, B. Pire, L. Szymanowski, SW [2212.00655, 2302.12026]

Moreover, the richer kinematics of the process allows the sensitivity of GPDs wrt x to be probed (beyond moment-type dependence, e.g. in DVCS):
J. Qiu, Z. Yu [2305.15397]

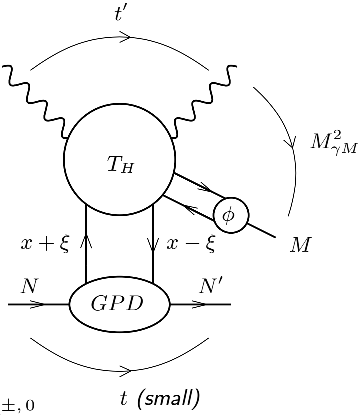
Probing GPDs using ρ or π meson + photon production

- We consider the process $\gamma\, N \rightarrow \gamma\, M\, N'$ M = meson
- Collinear factorization of the amplitude for $\gamma + N \rightarrow \gamma + M + N'$ at large $M^2_{\gamma M}$, t', u' and small t



large angle factorization
à la Brodsky Lepage

$\rightarrow$

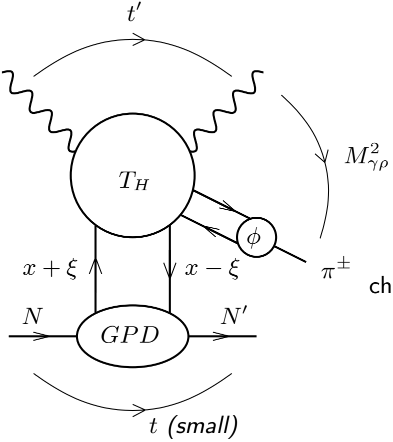


- Mesons considered in the final state: $\pi^{\pm}$, $\rho^{\pm,0}_{L,T}$

- Leading order and leading twist

Probing chiral-even GPDs using π meson + photon production

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

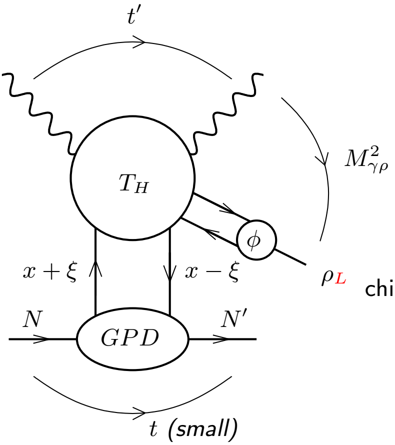


chiral-even twist 2 DA

chiral-even twist 2 GPD

Probing chiral-even GPDs using ρ_L meson + photon production

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

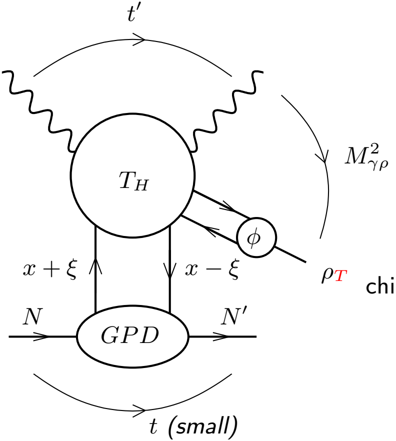


chiral-even twist 2 DA

chiral-even twist 2 GPD

Probing chiral-odd GPDs using ρ_T meson + photon production

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



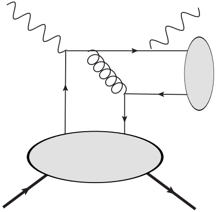
ρ_T chiral-odd twist 2 DA

chiral-odd twist 2 GPD

Probing chiral-odd GPDs using $\rho_T\ \gamma$ 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?



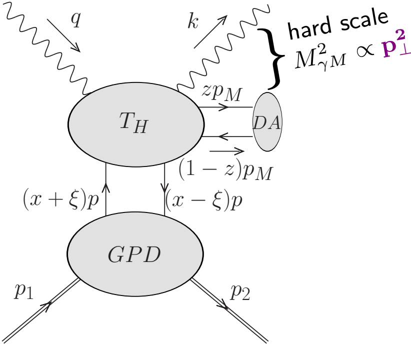
Typical LO non-zero diagram for a transverse ρ meson

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

Computation
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:
  - $\Delta_\perp \ll \mathbf{p}_\perp$
  - $M^2,\ m_M^2 \ll M_{\gamma M}^2$



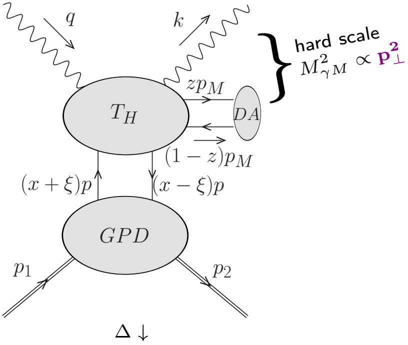
$\Delta \downarrow$

- initial state particle momenta:
  $q^\mu = n^\mu,\ p_1^\mu = (1+\xi)\,p^\mu + \frac{M^2}{s(1+\xi)}n^\mu$
- final state particle momenta:

$$
\begin{aligned}
p_2^\mu &= (1-\xi)\,p^\mu + \frac{M^2+\vec{p}_t^{\,2}}{s(1-\xi)}n^\mu + \Delta_\perp^\mu \\
k^\mu &= \alpha\,n^\mu + \frac{(\vec{p}_t-\vec{\Delta}_t/2)^2}{\alpha s}p^\mu + \mathbf{p}_\perp^\mu - \frac{\Delta_\perp^\mu}{2}\,, \\
p_M^\mu &= \alpha_M\,n^\mu + \frac{(\vec{p}_t+\vec{\Delta}_t/2)^2+m_M^2}{\alpha_M s}p^\mu - \mathbf{p}_\perp^\mu - \frac{\Delta_\perp^\mu}{2}\,,
\end{aligned}
$$

Computation
Kinematics

$$\gamma(q) + N(p_1) \rightarrow \gamma(k) + M(p_M, \varepsilon_M) + N'(p_2)$$



Useful Mandelstam variables:

$$t = (p_2 - p_1)^2\,,$$
$$u' = (p_M - q)^2\,,$$
$$t' = (k - q)^2\,,$$
$$S_{\gamma N} = (q + p_1)^2\,.$$

- Factorisation requires:

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

  $\Longrightarrow$ sufficient to ensure large $\mathbf{p_T}$

- Cross-section differential in $(-u')$ and $M^2_{\gamma M}$, and evaluated at $(-t) = (-t)_{\min}$, covering $S_{\gamma N}$ from $\sim 4\,\mathrm{GeV}^2$ to $20000\,\mathrm{GeV}^2$

Computation

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 :

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

Computation

Non perturbative chiral-odd building blocks

- Helicity flip GPD at twist 2 :

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

$$= \frac{1}{2P^+} \bar{u}(p_2, \lambda_2) \left[H_T^q(x,\xi,t) i\sigma^{+i} + \tilde{H}_T^q(x,\xi,t) \frac{P^+\Delta^i - \Delta^+ P^i}{M_N^2} \right.$$

$$\left. + \quad E_T^q(x,\xi,t) \frac{\gamma^+\Delta^i - \Delta^+\gamma^i}{2M_N} + \tilde{E}_T^q(x,\xi,t) \frac{\gamma^+ P^i - P^+\gamma^i}{M_N} \right] u(p_1, \lambda_1)$$

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

- Transverse ρ DA at twist 2 :

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

Computation

Parametrising the GPDs: 2 scenarios for polarised and transversity PDFs

Quark GPDs are parametrised in terms of Double Distributions

[A. Radyushkin: hep-ph/9805342]

For polarised PDFs Δq (and hence transversity PDFs δq), 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.

Computation
DAs used

- We take the simplistic asymptotic form of the DAs

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

- We also investigate the effect of using a holographic DA:

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

Suggested by

- AdS/QCD correspondence [S. Brodsky, G. de Teramond: hep-ph/0602252],
- dynamical chiral symmetry breaking on the light-front [C. Shi, C. Chen, L. Chang, C. Roberts, S. Schmidt, H, Zong: 1504.00689],
- recent lattice results. [X. Gao, A. Hanlon, N. Karthik, S. Mukherjee, P. Petreczky, P. Scior, S. Syritsyn, Y. Zhao: 2206.04084]

Computation

Method

$$\mathcal{A} = \int_{-1}^{1} dx \int_{0}^{1} dz \; T_H(x,\xi,z) \; GPD(x,\xi,t) \; \Phi_M(z)$$

- Differential cross section:

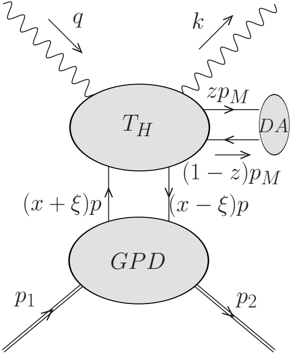
$$\left.\frac{d\sigma}{dt\,du'\,dM^2_{\gamma M}}\right|_{-t=(-t)_{min}} = \frac{|\overline{\mathcal{A}}|^2}{32 S^2_{\gamma N} M^2_{\gamma M} (2\pi)^3} \, .$$

- Kinematic parameters: $S_{\gamma N}$, $M^2_{\gamma M}$, $-t$, $-u'$

- Useful dimensionless variables (hard part):

$$\alpha = \frac{-u'}{M^2_{\gamma M}} \, ,$$

$$\xi = \frac{M^2_{\gamma M}}{2\left(S_{\gamma N} - m_N^2\right) - M^2_{\gamma M}} \, .$$



oCmputation

Is QCD collinear factorisation really justified?

- Recently, factorisation has been proved for the process $\pi N \to \gamma\gamma N'$ by J. Qiu, Z. Yu [2205.07846].
- This was extended to a wide range of $2 \to 3$ exclusive processes by J. Qiu, Z. Yu [2210.07995]
- The proof relies on having large p_T, rather than large invariant mass (e.g. photon-meson pair).
- In fact, NLO computation has been performed for $\gamma N \to \gamma\gamma N'$ by O. Grocholski, B. Pire, P. Sznajder, L. Szymanowski, J. Wagner [2110.00048, 2204.00396]
- Also, NLO computation for $\gamma\gamma \to \pi^+\pi^-$ by crossing symmetry G. Duplancic, B. Nizic: [hep-ph/0607069].

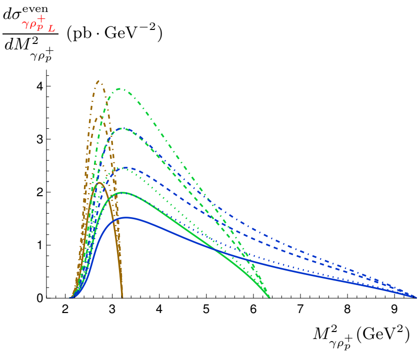
Issues with exclusive $\pi^0\gamma$ photoproduction which allows for **gluonic exchange in $t-$channel**:

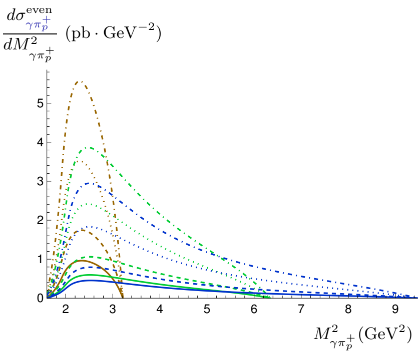
violation of collinear factorization at twist 2 due to Glauber gluons!

S. Nabeebaccus, J. Schönleber, L. Szymanowski, S. W: [2311.09146] (to appear in PRD); [2409.16067]

Results
Single differential cross-section

$\gamma\rho^+_{p\,L}$ versus $\gamma\pi^+_p$





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

Dashed: Holographic DA   non-dashed: Asymptotical DA

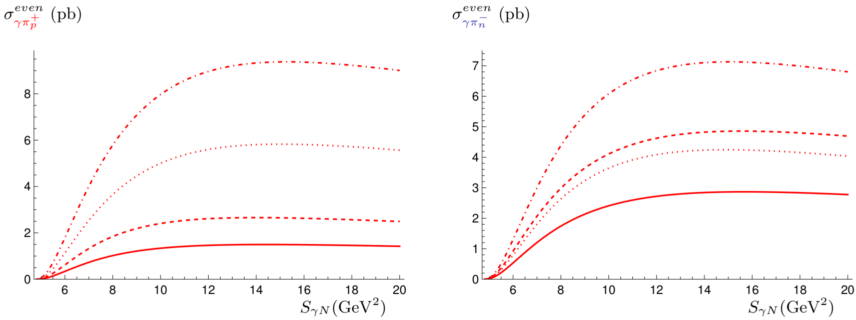
Dotted: standard scenario   non-dotted: valence scenario

$\Longrightarrow$ Effect of GPD model more important on π^+_p than on ρ^+_p

Results

Integrated cross-section

$\gamma\pi_p^+$ versus $\gamma\pi_n^-$



Dashed: Holographic DA non-dashed: Asymptotical DA

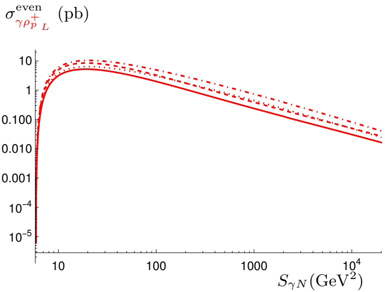
Dotted: standard scenario non-dotted: valence scenario

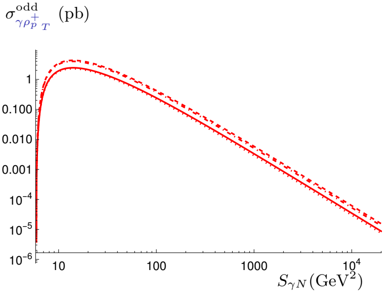
$\Longrightarrow$ Huge effect from GPD model in π_p^+ case.

Results

Integrated cross-section

$\gamma\rho^+_{p\ L}$ versus $\gamma\rho^+_{p\ T}$





Dashed: Holographic DA non-dashed: Asymptotical DA

Dotted: standard scenario non-dotted: valence scenario

$\Longrightarrow$ ξ^2 suppression in the chiral-odd case causes the cross-section to drop rapidly with $S_{\gamma N}$ ($\xi \approx \frac{M^2_{\gamma\rho}}{2S_{\gamma N}}$).

Results

Polarisation Asymmetries wrt incoming photon

We consider an unpolarised target, and determine polarisation asymmetries wrt the incoming photon.

- Circular polarisation asymmetry = 0 (QCD/QED invariance under parity)
- Linear polarisation asymmetry:

$$\mathrm{LPA} = \frac{d\sigma_x - d\sigma_y}{d\sigma_x + d\sigma_y}$$

  x = direction defined by $p_\perp$ (direction of outgoing photon in the $\perp$ plane)

- In fact,

$$\mathrm{LPA}_{\mathrm{Lab}} = \mathrm{LPA}\cos(2\theta) \; ,$$

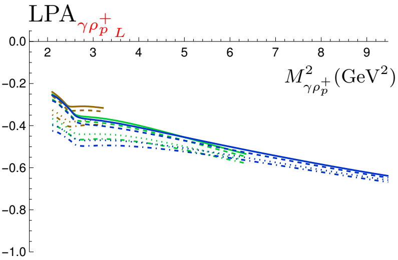
  where θ is the angle between the lab frame x-direction and $p_\perp$.

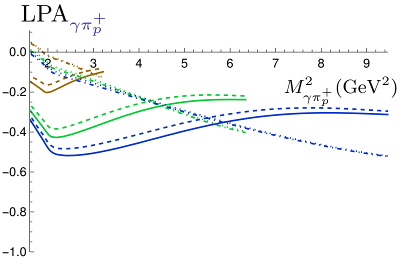
- Kleiss-Stirling spinor techniques used to obtain expressions.
- Both asymmetries are zero in chiral-odd case!

Results

LPA wrt incoming photon: Single-differential level

$\gamma \rho_{p\ L}^{+}$ versus $\gamma \pi_p^{+}$





$S_{\gamma N} = 8,\ 14,\ 20\ \mathrm{GeV}^2$

Dashed: Holographic DA non-dashed: Asymptotical DA

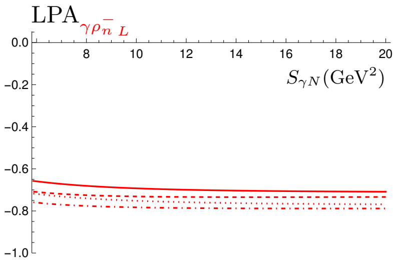
Dotted: standard scenario non-dotted: valence scenario

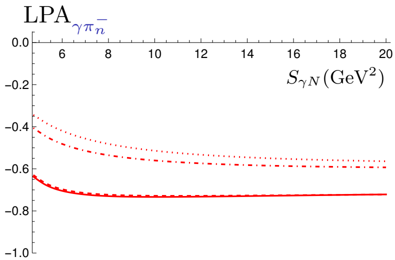
$\Longrightarrow$ GPD model changes the behaviour of the LPA completely in the π_p^+ case!

Results

LPA wrt incoming photon: Integrated level

$\gamma\rho^-_{n\ L}$ versus $\gamma\pi^-_n$





Dashed: Holographic DA non-dashed: Asymptotical DA

Dotted: standard scenario non-dotted: valence scenario

$\Rightarrow$ LPAs are sizeable!

Prospects at experiments

Counting rates: JLab

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:
  - ρ_L^0 (on p) $: \approx 2.4 \times 10^5$
  - ρ_T^0 (on p) $: \approx 4.2 \times 10^4$ (Chiral-odd)
  - $\rho_L^+ : \approx 1.4 \times 10^5$
  - $\rho_T^+ : \approx 6.7 \times 10^4$ (Chiral-odd)
  - $\pi^+ : \approx 1.8 \times 10^5$
- No problem in detecting outgoing photon at JLab.

Prospects at experiments

Counting rates: EIC

- At the future EIC, with an expected integrated luminosity of $10\,\mathrm{fb}^{-1}$ (about 100 times smaller than JLab):
  - ρ^0_L (on p) : $\approx 2.4 \times 10^4$
  - ρ^0_T (on p) : $\approx 2.4 \times 10^3$ (Chiral-odd)
  - ρ^+_L : $\approx 1.5 \times 10^4$
  - ρ^+_T : $\approx 4.2 \times 10^3$ (Chiral-odd)
  - π^+ : $\approx 1.3 \times 10^4$

- Small ξ study:

  $300 < S_{\gamma N}/\mathrm{GeV}^2 < 20000$ ($5 \cdot 10^{-5} < \xi < 5 \cdot 10^{-3}$):
  - ρ^0_L (on p) : $\approx 1.2 \times 10^3$
  - ρ^0_T (on p) : ≈ 6.5 (Chiral-odd) (tiny)
  - ρ^+_L : $\approx 9.3 \times 10^2$
  - π^+ : $\approx 5.0 \times 10^2$

Prospects at experiments
LHC at UPC

For p-Pb UPCs at LHC (integrated luminosity of 1200 nb^{-1}):

- With future data from runs 3 and 4,
  - $\rho_L^0 : \approx 1.6 \times 10^4$
  - $\rho_T^0 : \approx 1.7 \times 10^3$ (Chiral-odd)
  - $\rho_L^+ : \approx 1.1 \times 10^4$
  - $\rho_T^+ : \approx 2.9 \times 10^3$ (Chiral-odd)
  - $\pi^+ : \approx 9.3 \times 10^3$
- $300 < S_{\gamma N}/\mathrm{GeV}^2 < 20000$ ($5 \cdot 10^{-5} < \xi < 5 \cdot 10^{-3}$):
  - $\rho_L^0 : \approx 8.1 \times 10^2$
  - $\rho_L^+ : \approx 6.4 \times 10^2$
  - $\pi^+ : \approx 3.4 \times 10^2$

Conclusions

- Exclusive photoproduction of photon-meson pair provides additional channel for extracting GPDs: Interesting effects from choice of different mesons, access to chiral-odd GPDs at the leading twist
- Especially interesting since it can probe chiral-odd GPDs at the leading twist, and provides better sensitivity to x-dependence of GPDs
- Proof of factorisation for this family of processes now available, but $\pi^0\gamma$ photoproduction suffers from collinear factorisation breaking effects at the leading twist
- Good statistics in various experiments, particularly at JLab
- Small ξ limit of GPDs can be investigated by exploiting high energies available in collider mode such as EIC and UPCs at LHC.

Outlook

- Compute $\gamma N \to \gamma \pi^0 N$ in high-energy (k_T) factorisation [ongoing]
- Compute NLO corrections (422 NLO diagrams, vs 20 LO diagrams!). Careful treatment of $i\epsilon$ factors in denominators [ongoing]
- Generalise to electroproduction $(Q^2 \neq 0)$
- Add Bethe-Heitler component (photon emitted from incoming lepton)
  - zero in chiral-odd case
  - suppressed in chiral-even case
- A similar process, with two mesons in the final state, is very promising

  For $\pi^+ \rho_T^0$, see: B. Pire, M El Beyiad, L. Szymanowski, S. W: [1001.4491]

  Extension to any pair of light meson:
  [ongoing: D. Perez, S. Nabeebaccus, L. Szymanowski, S. W]