Round Table on Nuclear GPDs

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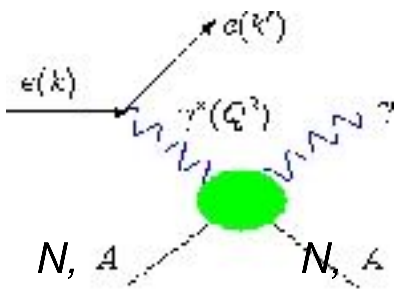
Outline:

- Basics of generalized parton distributions (GPDs)
- GPD phenomenology at high energies
- Nuclear GPDs at high energies
- Summary

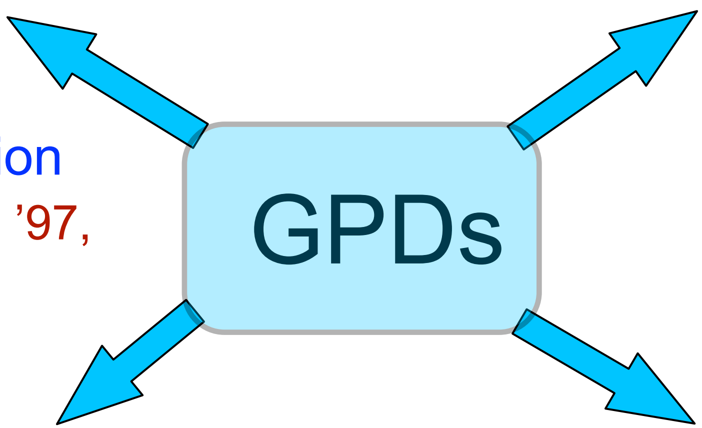
Factorization for exclusive processes

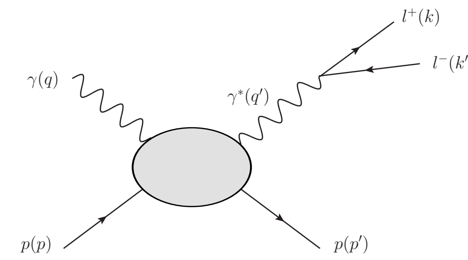
- Factorization for hard exclusive processes allows us to describe different processes using the same set of universal GPDs:



DVCS, J/ψ, ϱ, π production

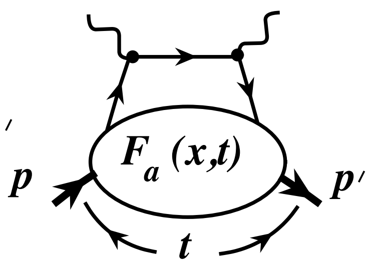
Collins, Frankfurt, Strikman ’97,
Collins, Freund ’99





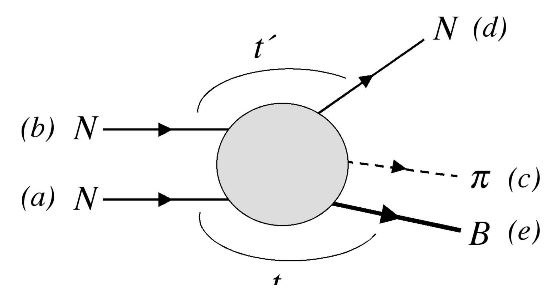
Timelike Compton scattering

Berger, Diehl, Pire ’02



Wide angle Compton scattering (?)

Radyushkin ’98,
Diehl, Feldman, Jacob, Kroll ’99

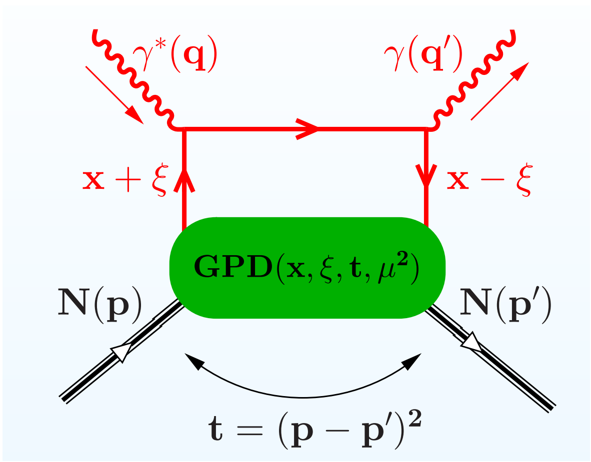


Hard hadron-initiated processes

Kumano, Strikman, Sudoh ’09

Factorization for DVCS

• At sufficiently large Q^2 and fixed t, the DVCS amplitude factorized into a hard (perturbative) part and a soft (non-perturbative) part:



• x and ξ are quark light-cone fractions:
ξ is fixed by kinematics $\xi \approx \frac{x_B}{2-x_B}$
x is integrated over

• $t=(p-p')^2$

• μ^2 is the factorization scale

• The DVCS hadronic tensor:

$$
\begin{aligned}
H^{\mu\nu} = &\ \frac{1}{2}(-g^{\mu\nu})_\perp \int_{-1}^{1} dx\, C^+(x,\xi)\Big[H\,\bar{u}(p')\hat{n}u(p) + E\,\bar{u}(p')i\sigma^{k\lambda}\frac{n_k\Delta_\lambda}{2m_N}u(p)\Big] \\
+ &\ \frac{i}{2}(\epsilon^{\nu\mu})_\perp \int_{-1}^{1} dx\, C^-(x,\xi)\Big[\tilde{H}\,\bar{u}(p')\hat{n}\gamma_5 u(p) + \tilde{E}\,\bar{u}(p')\gamma_5\frac{\Delta\cdot n}{2m_N}u(p)\Big]
\end{aligned}
$$

where the hard part is $C^{\pm} = \frac{1}{x-\xi+i\epsilon} \pm \frac{1}{x+\xi-i\epsilon}$

Müller, Robaschik, Geyer, Dittes, Horejsi ’94,
Radyushkin ’96
Ji ’97

Properties of GPDs

- Connection to usual parton distributions in the forward limit $\xi = t = 0$:

$$H^q(x,0,0) = q(x)$$
$$H^q(x,0,0) = -\bar{q}(-x)$$

x > 0
x < 0

$$\tilde{H}^q(x,0,0) = \Delta q(x)$$
$$\tilde{H}^q(x,0,0) = \Delta \bar{q}(-x)$$

Note: NO corresponding relations for GPDs E and E~.

- Connection to the nucleon elastic form factors:

$$\int_{-1}^{1} dx\, H^q(x,\xi,t) = F_1^q(t), \qquad \int_{-1}^{1} dx\, E^q(x,\xi,t) = F_2^q(t)$$
$$\int_{-1}^{1} dx\, \tilde{H}^q(x,\xi,t) = g_A^q(t), \qquad \int_{-1}^{1} dx\, \tilde{E}^q(x,\xi,t) = g_P^q(t)$$

- Polynomiality as a consequence of Lorentz invariance, e.g.:

$$\int_{-1}^{1} dx\, x^n\, H^q(x,\xi,t) = \sum_{i=0,\mathrm{even}}^{n} (2\xi)^i A^q_{n+1,i}(t) + \mathrm{mod}(n,2)(2\xi)^{n+1} C^q_{n+1}(t)$$

- Positivity as a consequence of unitarity $\longrightarrow$ upper bounds on GPDs

It is a challenge to construct a model/parameterization of GPDs satisfying all constraints.

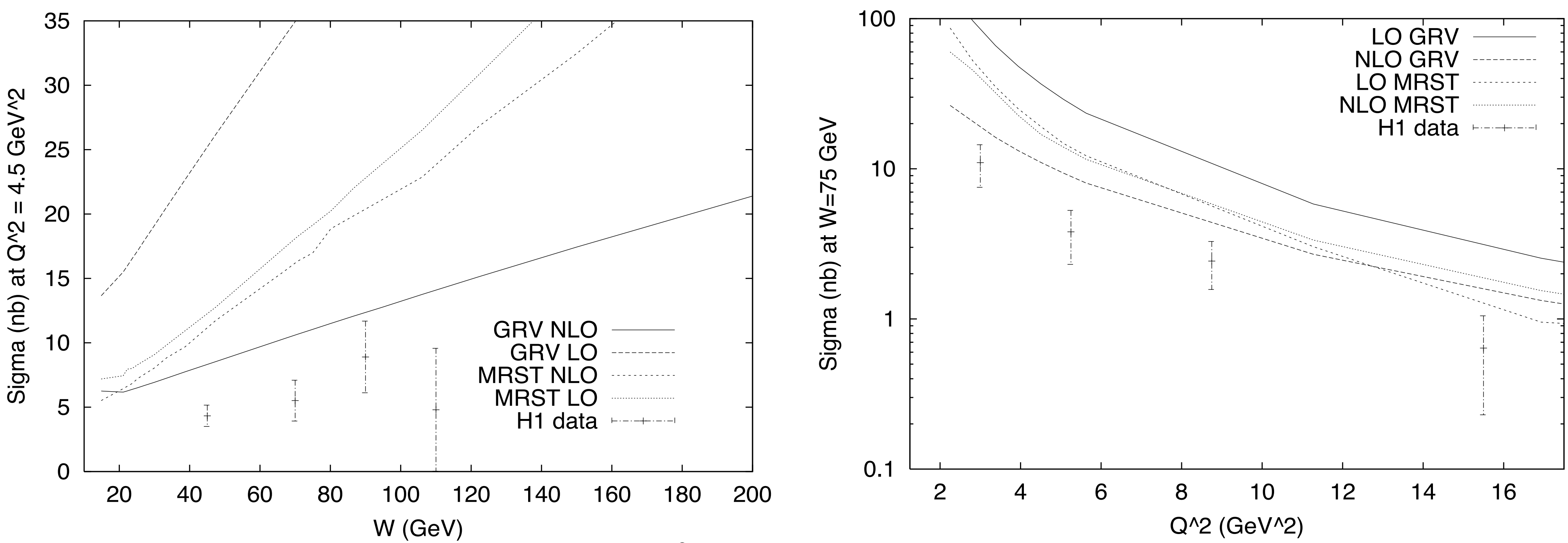
Double distribution vs. HERA DVCS data

• Radyushkin's double distribution (in old notation):

$$\mathcal{F}^{q,a}(X,\zeta) = \frac{2}{\zeta}\int_{\frac{v_1-\xi}{1-\xi}}^{\frac{v_1+\xi}{1+\xi}} dx'\pi^q\left(x', \frac{v_1-x'}{\xi}\right) q^a(x')$$

• The problem is that the integral probes PDFs down to very small x', where they have to extrapolated.

• As a result, NLO pQCD dramatically **overestimates** the HERA data on ep DVCS cross section, Freund, McDermott, EPJC 23 (2002) 651, 011472 [hep-ph]

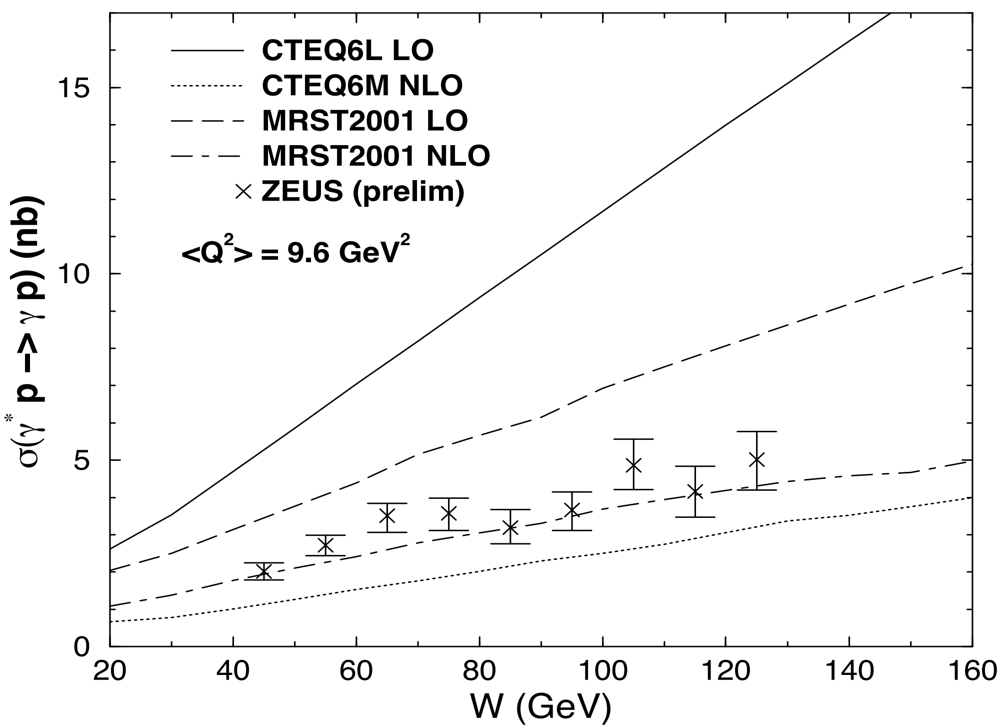


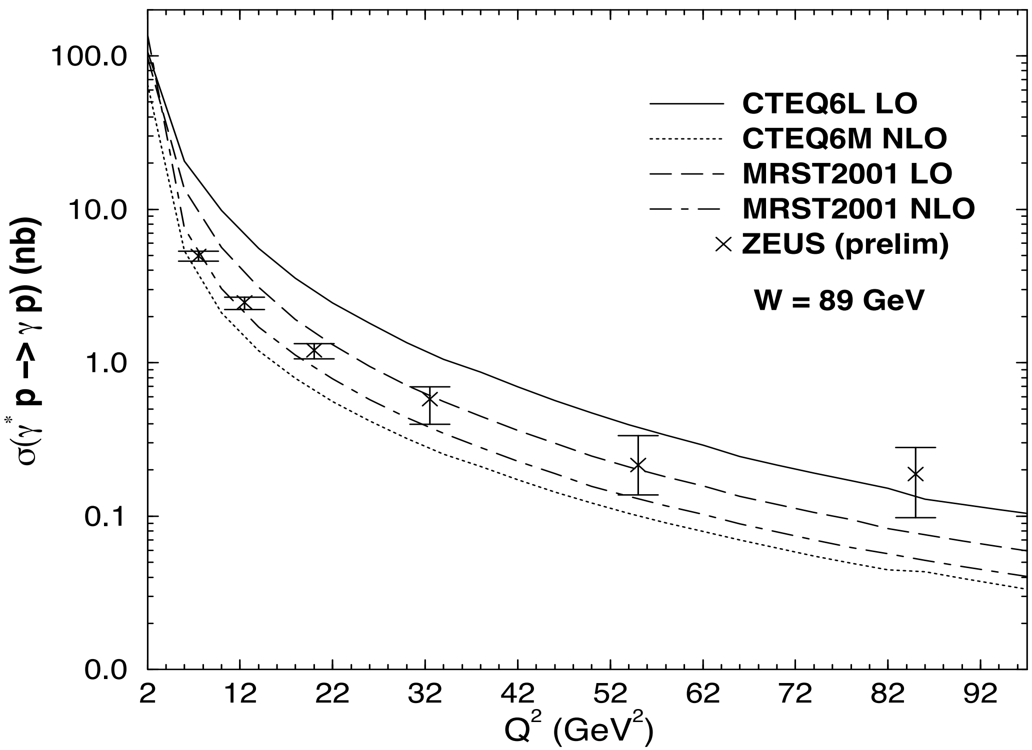
Forward model vs. HERA DVCS data

- Forward model for GPDs, Freund, McDermott, Strikman, PRD 67 (2003) 036001, 0208160 [hep-ph]:

$$H^S(v,\xi) = q^S(v) \equiv q^S\left(\frac{X-\zeta/2}{1-\zeta/2}\right)$$

- Reasonable NLO pQCD description of HERA data on DVCS cross section:





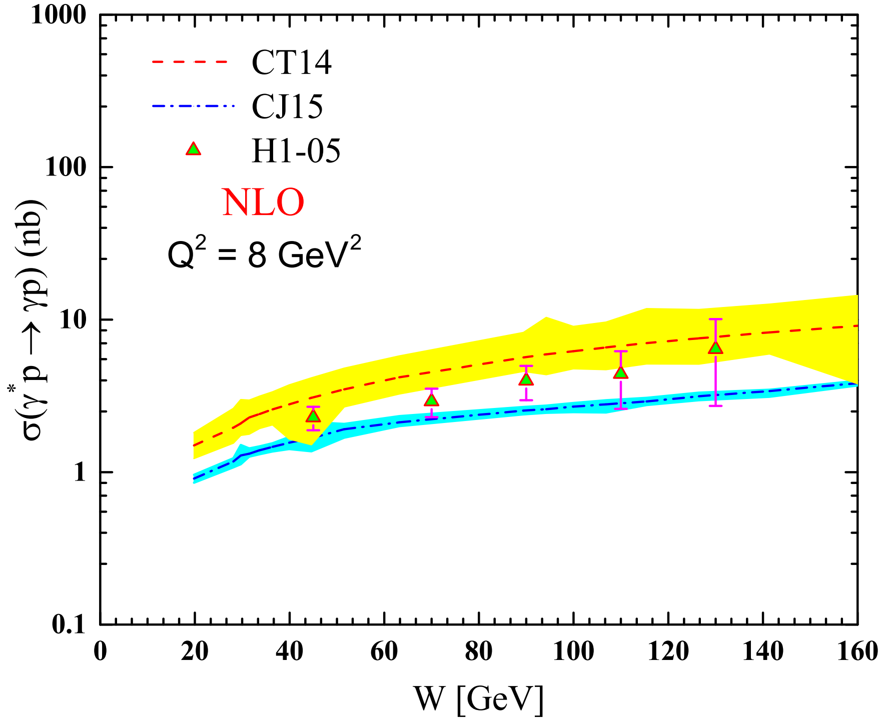
Forward model vs. HERA DVCS data (2)

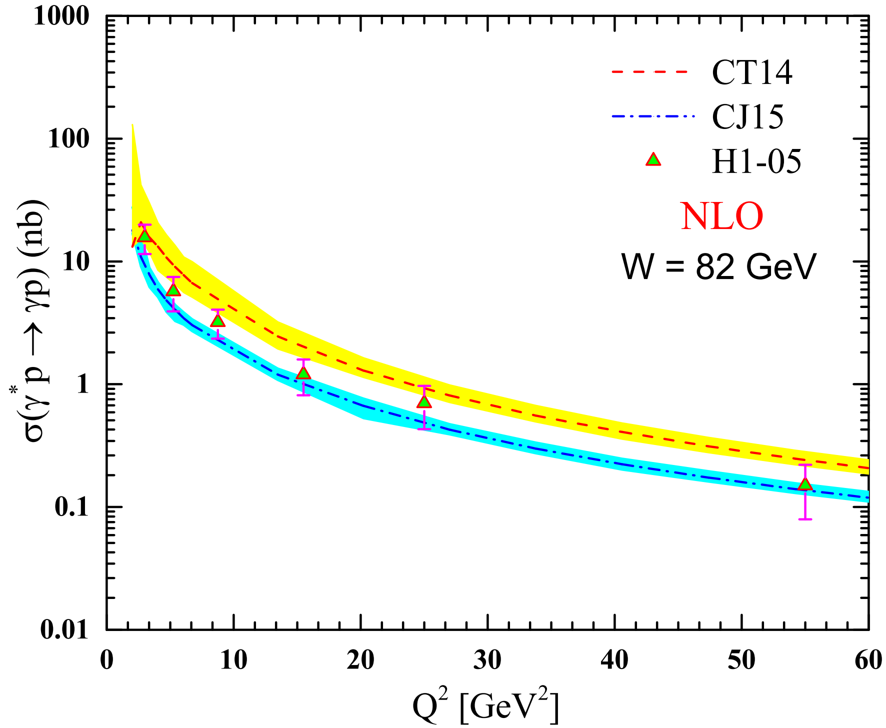
• Update on forward model for GPDs, Khanpour, Goharipour, Guzey, EPJ C 78 (2018) 1,7, 1708.05749 [hep-ph]

$$(1-\zeta/2)\,H^S(X,\zeta,t=0,\mu_0) =$$
$$\begin{cases} \sum_q [q(x,\mu_0)+\bar{q}(x,\mu_0)] + D^S\,(x/\eta)\,\theta(\zeta - X)\,, & X > \zeta/2 \\ -\sum_q [q(x,\mu_0)+\bar{q}(x,\mu_0)] - D^S\,(x/\eta)\,\theta(\zeta - X)\,, & X < \zeta/2 \end{cases}$$
$$(1-\zeta/2)\,H^g(X,\zeta,t=0,\mu_0) = |x| g(|x|,\mu_0)\,, \qquad (1)$$

• NLO coefficient functions and NLO Q^2 evolution of GPDs from code written by Freund and McDermott.

• Again, reasonable description of HERA data on DVCS cross section:





Flexible parametrization vs. HERA DVCS data

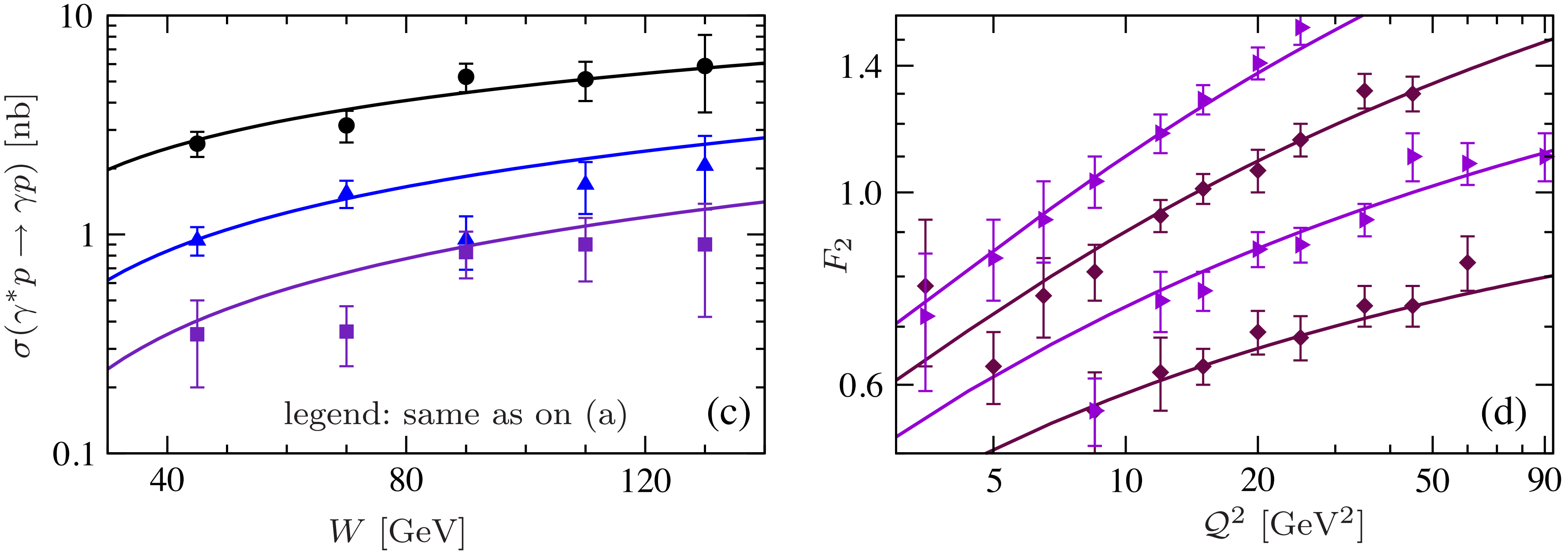
• GPDs as a series over Gegenbauer moments, Kumericki, Mueller, NPB 841 (2010) 1, 0904.0458 [hep-ph]

$$\boldsymbol{H}_j(\eta,t,\mu^2) = \frac{\Gamma(3/2)\Gamma(j+1)}{2^j\Gamma(j+3/2)}\frac{1}{2}\int_{-1}^{1} dx\ \eta^j \begin{pmatrix} C_j^{3/2} & 0 \\ 0 & \frac{3}{j}\frac{1}{\eta}C_{j-1}^{5/2} \end{pmatrix}\left(\frac{x}{\eta}\right)\boldsymbol{H}(x,\eta,t,\mu^2)$$

$$\boldsymbol{H}(x,\eta=x,t) = \frac{1}{2\pi i}\int_{c-i\infty}^{c+i\infty} dj\ \left(\frac{x}{2}\right)^{-1-j}\frac{\Gamma(5/2+j)}{\Gamma(3/2)\Gamma(3+j)}\begin{pmatrix} 1 & 0 \\ 0 & 2x/(3+j) \end{pmatrix}\boldsymbol{H}_j(\eta=x,t)$$

• Main advantage: solves Q^2 evolution of GPDs at LO and NLO* (in a special scheme) + polynomiality by construction → in spirit of Mellin moments of usual PDFs.

• Flexible parametrization: free parameters fitted to DIS and DVCS data.



Nuclear GPDs at small ξ ≈ nPDFs

• GPDs are hybrid distributions interpolating between usual PDFs, distribution amplitudes and form factors → depend on momentum fractions x and ξ, mom. transfer t, and scale μ → connection to PDFs and is model-dependent.

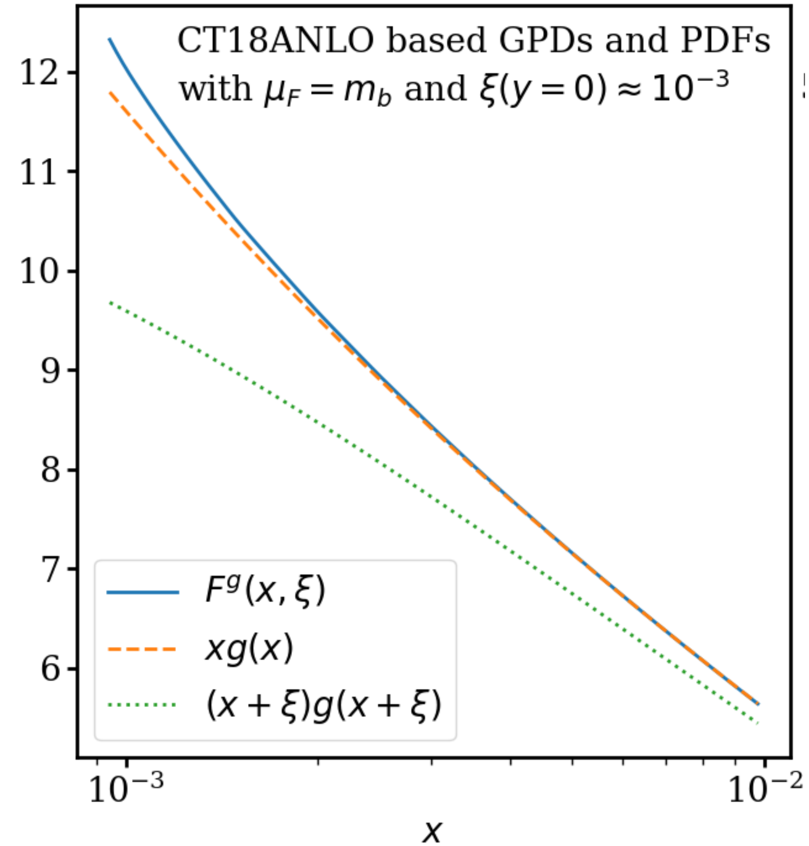
• However, at small ξ, GPDs can be expressed in terms of PDFs because μ^2 evolution washes out information on ξ-dependence, Shuvaev, Golec-Biernat, Martin, Ryskin, PRD 60 (1999) 014015; Dutrieux, Winn, Bertone, arXiv:2302.07861 [hep-ph].

• Numerically, with a few % accuracy, one can use for nuclear GPDs, Eskola, Flett, Guzey, Löytäinen, Paukkunen, arXiv:2303.03007 [hep-ph]

$$F_A^g(x,\xi,t,\mu_F) = xg_A(x,\mu_F)F_A(t)$$

Nuclear PDFs (EPPS16, EPPS21, nCTEQ15 nNNPDF3.0)

Nucleus form factor (Woods-Saxon)



Summary

• At high energies (small skewness ξ), GPDs cannot deviate strongly from PDFs due to polynomiality.

• In addition, Q^2 evolution washes out information on ξ-dependence of GPDs $\rightarrow$ further support for forward model: GPD(x,ξ,t)=PDF(x)*F_A(t).

• LTA improves on this approximation by predicting the t-dependent (impact parameter dependent b) nuclear shadowing, i.e., x and t are correlated, Guzey, Strikman, Zhalov, PRC 95 (2017) 2, 025204

$$g_A(x,t,\mu^2) = \int d^2\vec{b}\, e^{i\vec{q}_\perp \vec{b}} g_A(x,b,\mu^2) \neq \int d^2\vec{b} e^{iq_\perp \cdot \vec{b}} g_A(x) T_A(b) = g_A(x) F_A(t)$$