Accessing GPDs at LHeC

LHeC workshop , Chavannes-de-Bogis , June 2012

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based on work done with L Szymanowski, J Wagner, S. Wallon

Section 5.2.3 in LHeC report

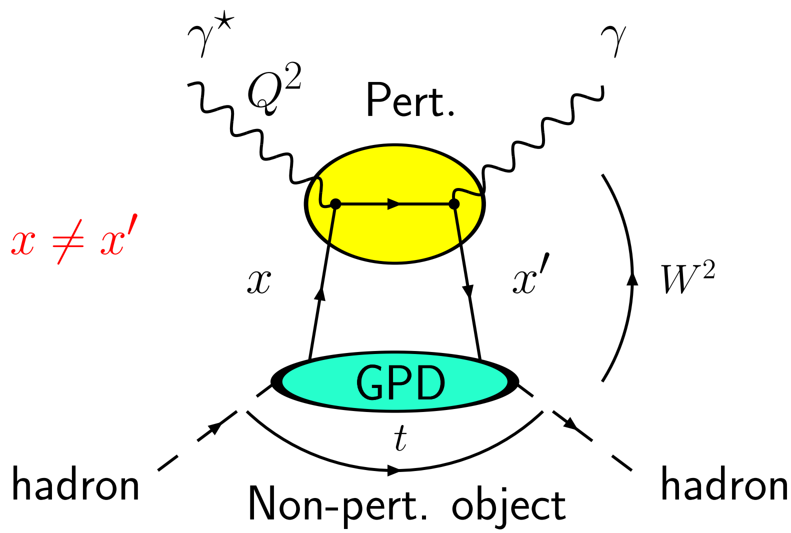
(Link to section 3 of EIC report : arXiv :1108.1713 [nucl-th])

Plan

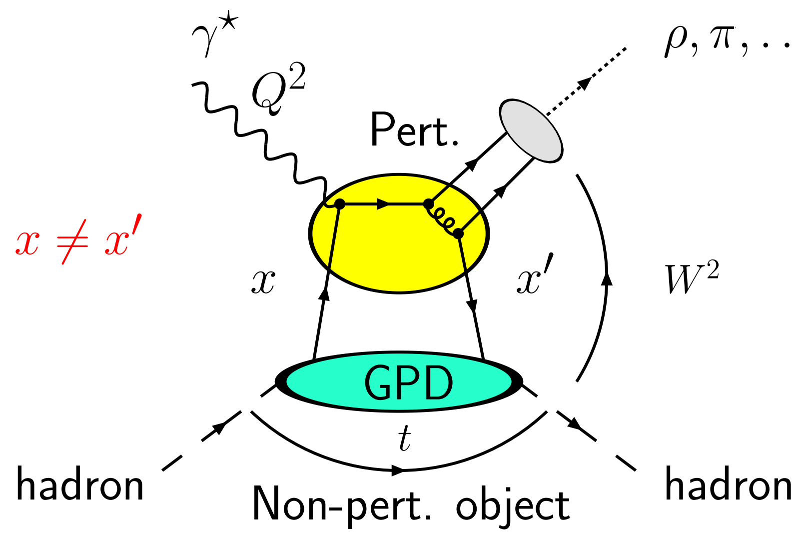
- QCD (colinear) factorization for exclusive reactions
  - * Success in DVCS : JLab, HERMES, HERA
  - → GPD properties ; transverse imaging of the nucleon
- DVCS and Timelike Compton scattering at very high energies
  - → NLO corrections ; higher twist contributions
  - → access in UPC at LHC ; access at LHeC
- Exclusive meson electroproduction, spin physics and chiral-odd GPDs
- k_T vs colinear factorization ; searching for the Odderon

QCD factorization in Exclusive processes

DVCS



Meson Production



➪ Factorisation between a hard part (perturbatively calculable) and a soft part (non-perturbative) *Generalized Parton Distribution* demonstrated for

$$Q^2, W^2 \to \infty,\ x_B = \frac{Q^2}{Q^2+W^2} \text{ fixed and } |t| \ll Q^2 \text{ fixed}$$

D. Mueller *et al.*, X. Ji, A. Radyushkin, J. Collins *et al.* , '94, '96,'98

Some very good news

The simplest hard exclusive process : $\gamma^*\gamma \to \pi^0$

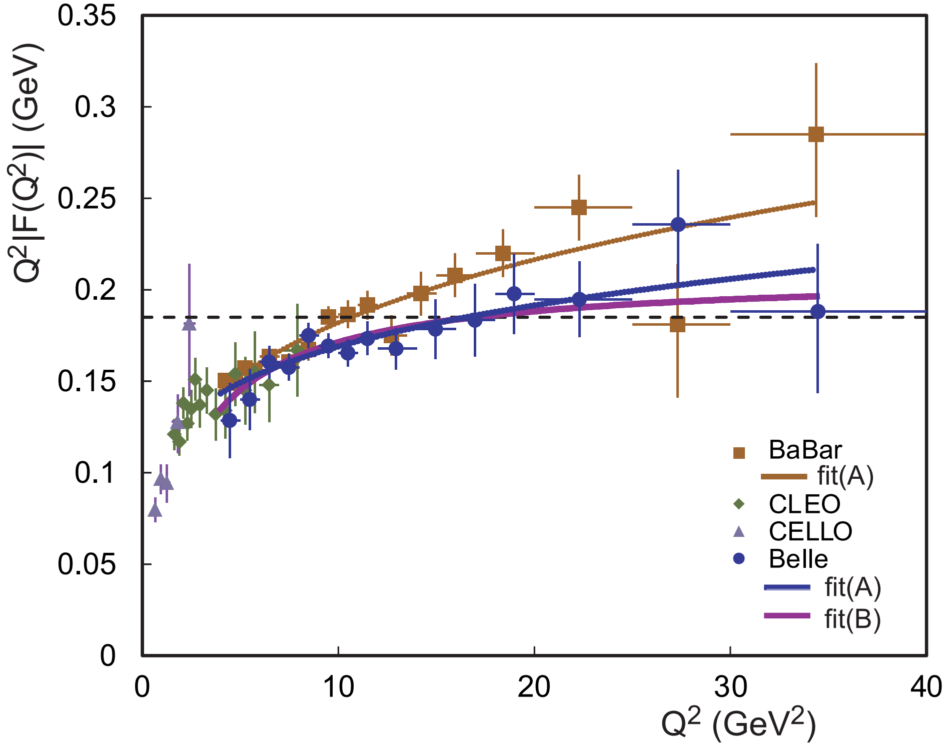


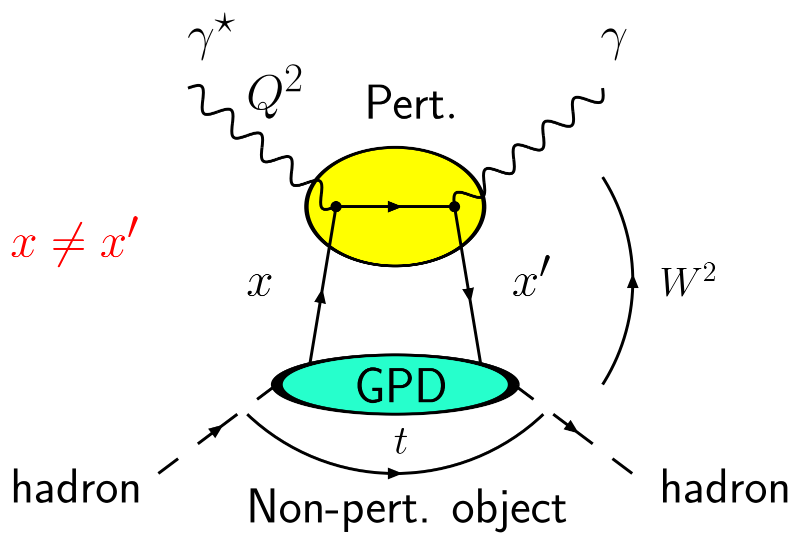
FIG. 24: Comparison of the results for the product $Q^2|F(Q^2)|$ for the π^0 from different experiments. The

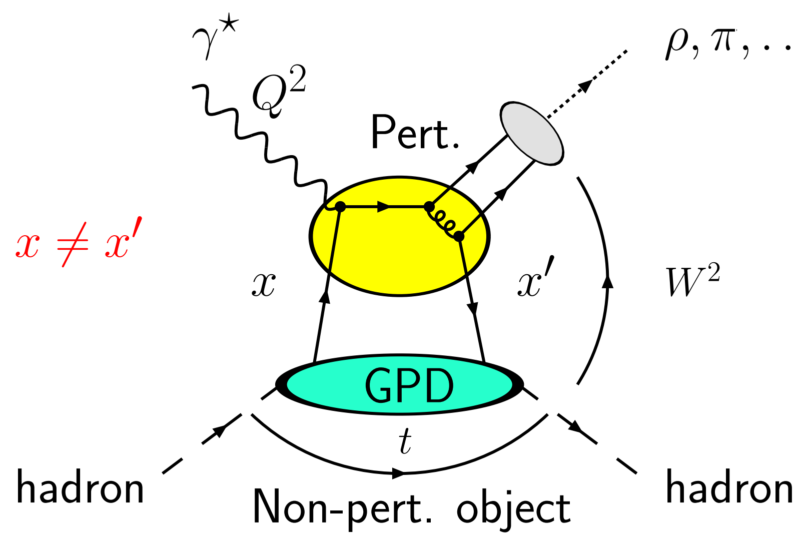
Belle confirms the applicability of perturbative QCD analysis to $\pi^0\gamma$ transition form factor

after BABAR data shaking the faith of theorists.

Generalised Parton Distributions

Non-Local operators (as in DIS) and non diagonal matrix elements = soft part of the amplitude for exclusive reactions





GPD (x, ξ, t) **= Fourier Transform of matrix elements**

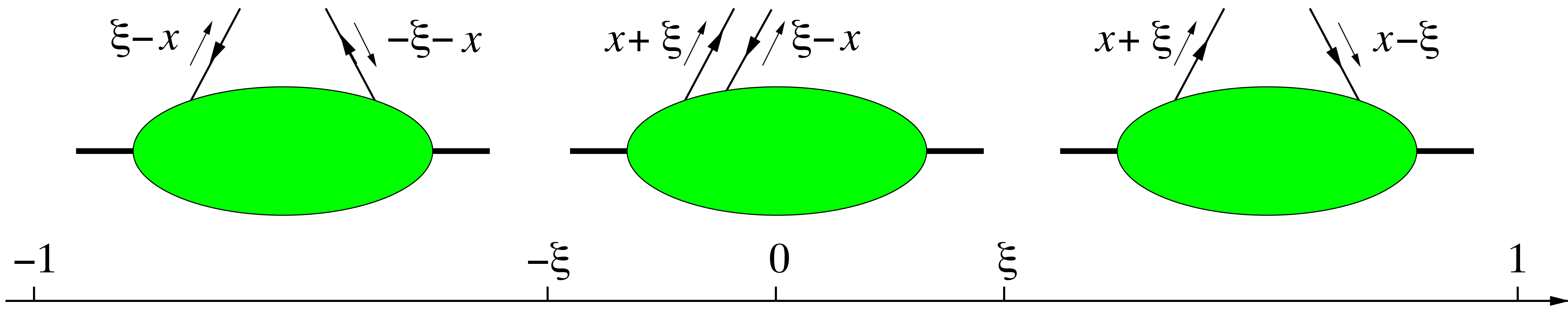
$$\langle N(p',\lambda')|\bar{\psi}(-z/2)_\alpha[-z/2;z/2]\psi(z/2)_\beta|N(p,\lambda)\rangle\Big|_{z^+=0,\, z_T=0}$$

ON THE LIGHT CONE $z^2 = 0$

$p' - p = \Delta \qquad \Delta^2 = t \qquad \Delta^+ = -\xi(p+p')^+ \qquad x - x' = 2\xi$

Energy flow in GPDs

Three different regions : mean momentum fraction x vs skewness ξ



antiquark content	$\bar{q}q$ content	quark content

Two different evolution equations

as $\bar{q}(-x, Q^2)$	as $\Phi^\pi(z, Q^2)$	as $q(x, Q^2)$
DGLAP	**ERBL**	**DGLAP**
$\rightarrow \delta(-x)$	$\rightarrow \Phi^\pi_{as}(z, Q^2) = 6z\bar{z}$	$\rightarrow \delta(x)$

Impact picture Representation

M. Burkhardt, JP Ralston and BP, M. Diehl

t dependence of GPDs maps transverse position b_T of quarks.

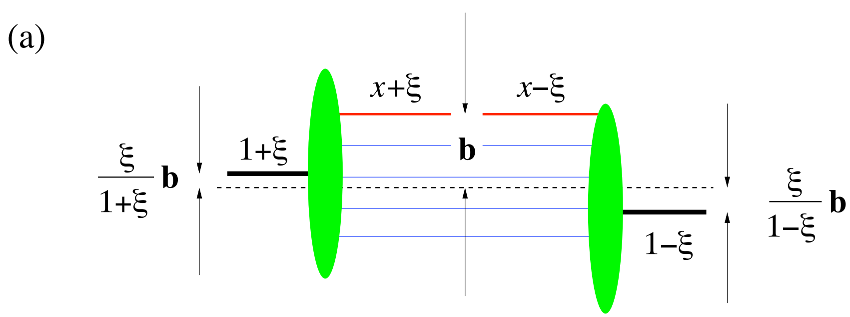
Fourier transform GPD at zero skewness

$q(x,b_T) = (2\pi)^{-2} \int d^2\Delta_T e^{i\Delta_T . b_T} H(x,\xi=0,t)$ probability

Generalize at $\xi \neq 0 \rightarrow$ Quantum femtophotography.

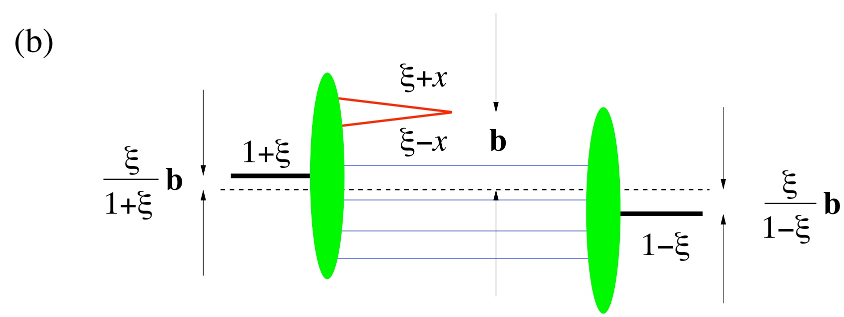
The $t-$dependence of dVCS localizes transversally in the proton the q and g (DGLAP) or the $\bar{q}q$ and gg pairs of size $\frac{1}{Q}$ (ERBL)

DGLAP region ($x > \xi$)



Femtophotography of quark in the proton

ERBL region ($x < \xi$)

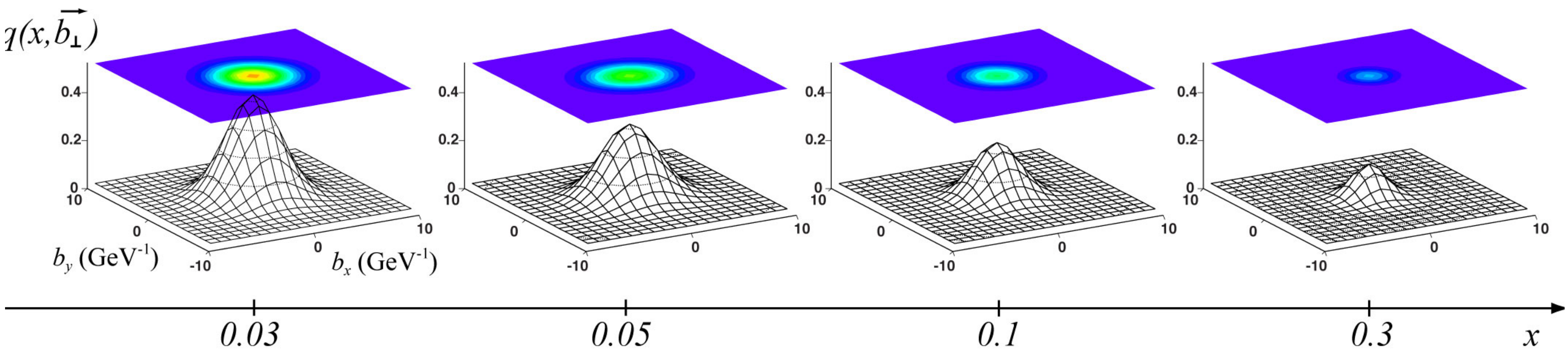


Femtophotography of quark-antiquark pair in the proton

Quark and Gluon imaging

Thanks to Franck Sabatié

Parton imaging with an EIC



for this dream to become textbook for students in the 2030's

one needs accurate measurement down to small values of ξ

$\rightarrow$ High energy, high luminosity electron nucleon colliders essential

This is the reason I consider GPDs as a major breakthrough in QCD physics

- **Beautiful progress in forward exclusive photon (DVCS) and meson (DVMP) experiments and analysis**

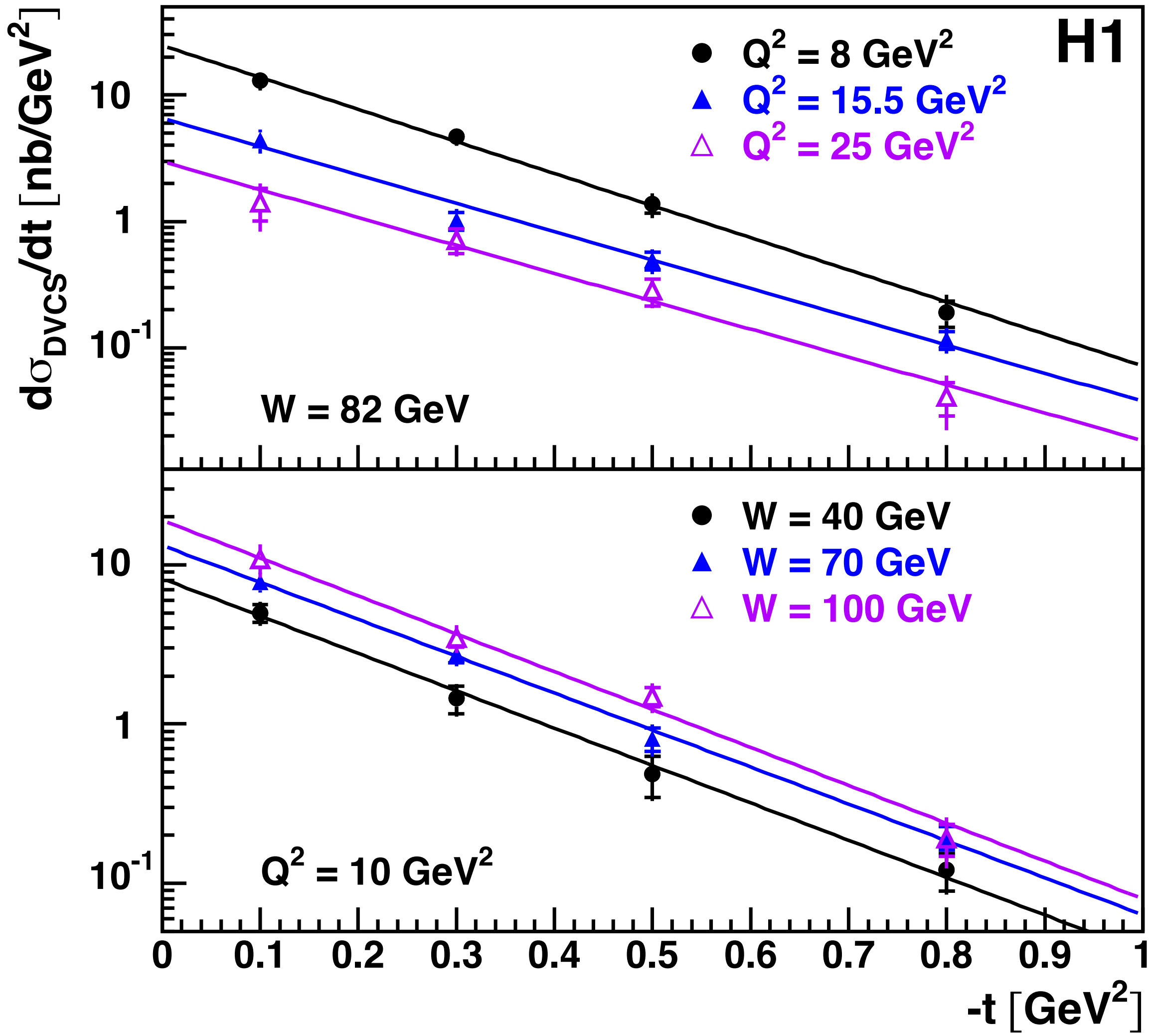
- **Need to test universality of GPDs : TCS vs DVCS extractions**

- **Need to better understand NLO and twist 3 contributions ($\rightarrow \rho_T$)**

- **Need to resum soft gluon contributions (Altinoluk *et al 2012*)**

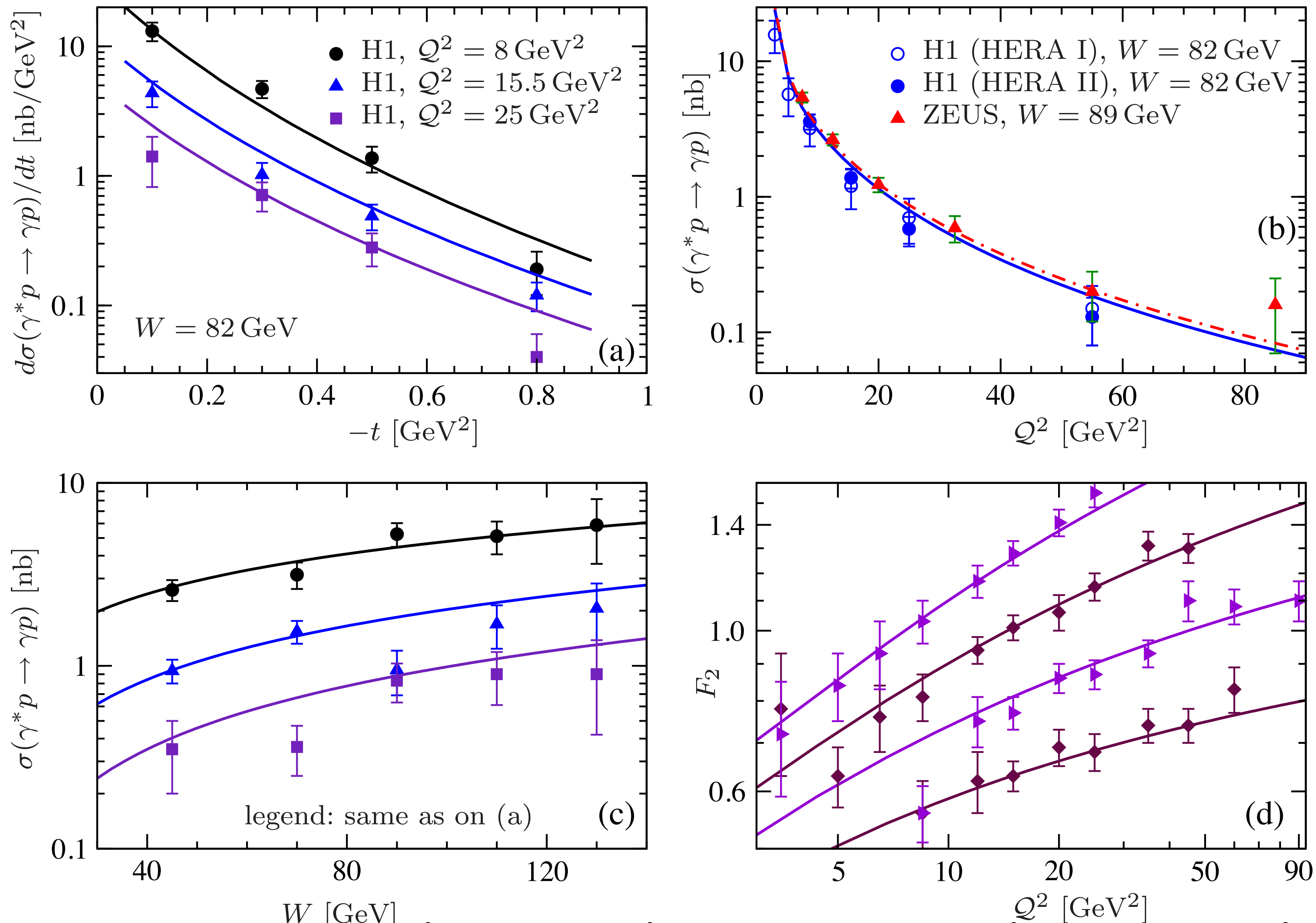
- **Need to go to higher energies, smaller skewness (EIC ; LHeC)**

HERA results on DVCS



I forget on purpose the beautiful data at lower energies from HERMES and JLab

Describing DVCS results with GPDs



Fitting DVCS (and DIS) with GPDs (and PDFs)

from K Kumericki and D. Mueler ArXiv 0904.0458

DVCS simulation for LHeC

for $\xi \approx x_B/2$ from $2\ 10^{-5}$ to $6\ 10^{-3}$ **(for 1 fb^{-1} luminosity)**

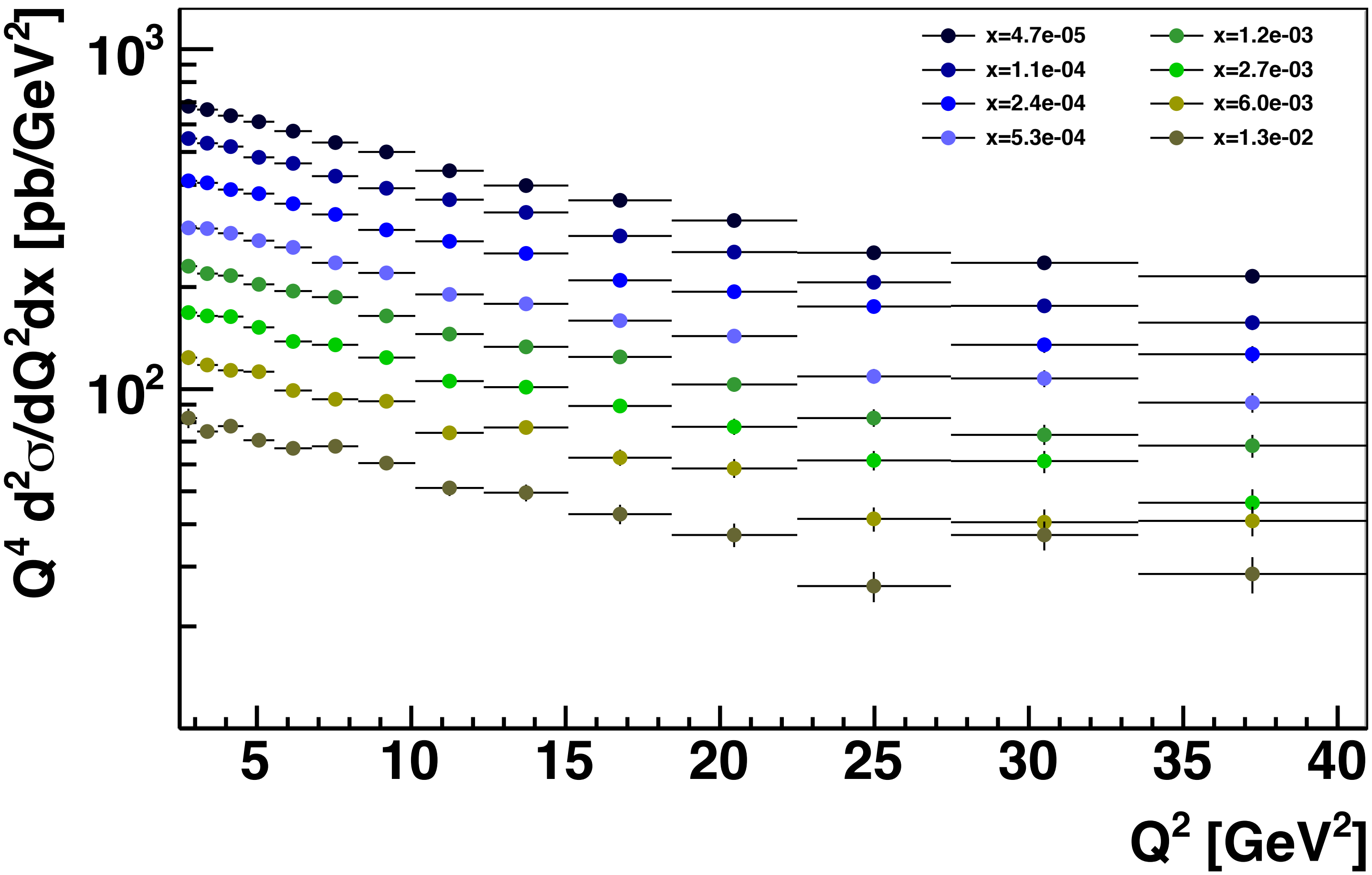


Figure 5.27: Simulated LHeC measurement of the DVCS cross section multiplied by Q^4 for different x values for a luminosity of 1 fb^{-1}, with $E_e = 50$ GeV, and electron and photon acceptance extending to within 1° of the beampipe with a cut at $P_T^\gamma = 2$ GeV. Only statistical uncertainties are considered.

and at very large Q^2

ξ **from** $6\ 10^{-5}$ **to** $4\ 10^{-3}$ **(for** 100 **fb**$^{-1}$ **luminosity)**

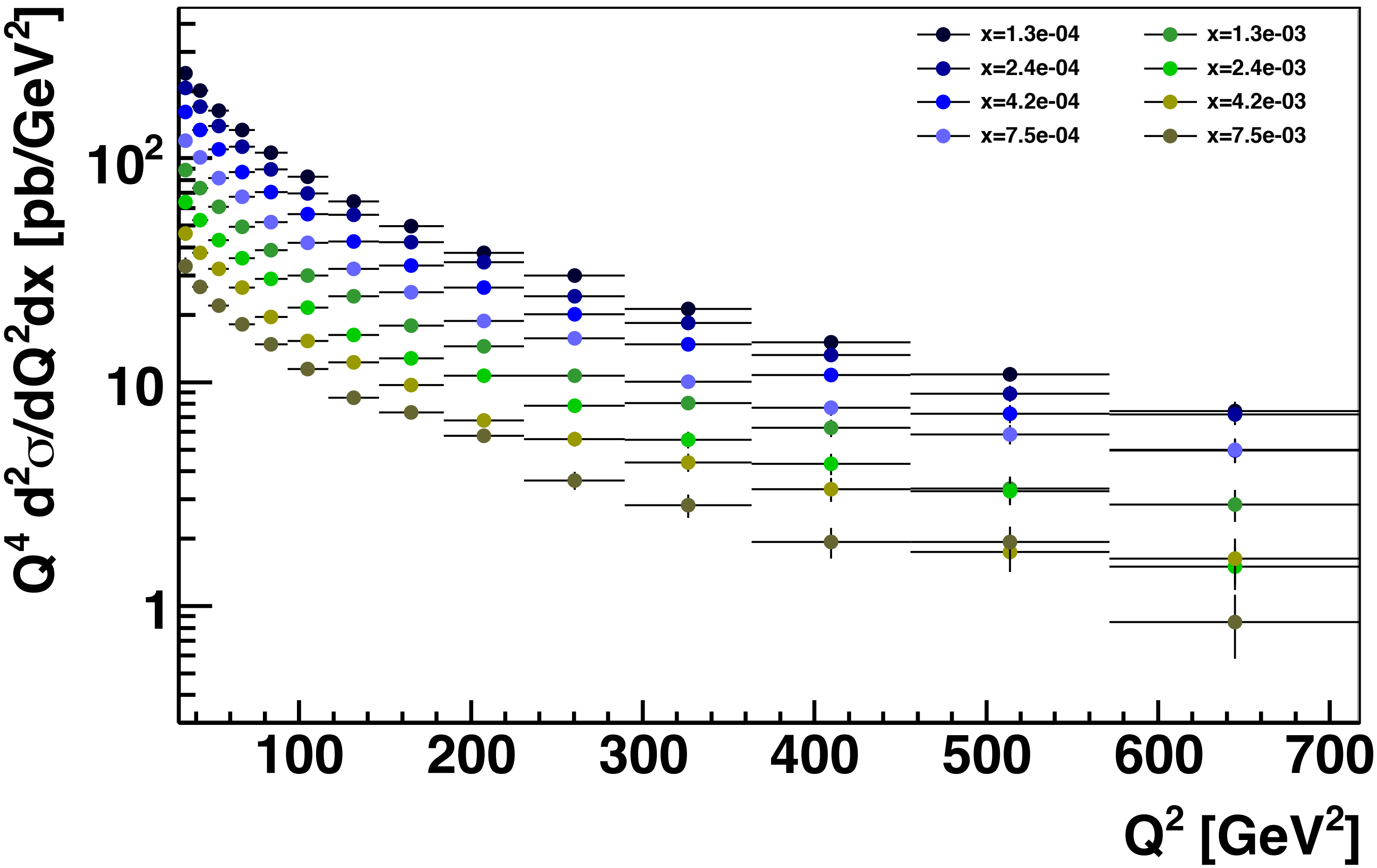
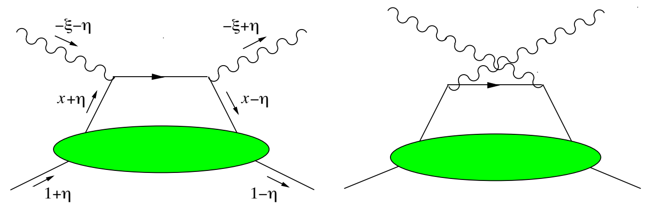


Figure 5.28: Simulated LHeC measurement of the DVCS cross section multiplied by Q^4 for different x values for a luminosity of 100 fb^{-1}, with $E_e = 50$ GeV, and electron and photon acceptance extending to within 10° of the beampipe with a cut at $P_T^\gamma = 5$ GeV. Only statistical uncertainties are considered.

On spacelike vs timelike probe

$\gamma^*(q) N(p) \to \gamma^*(q') N'(p')$ **DVCS vs TCS**

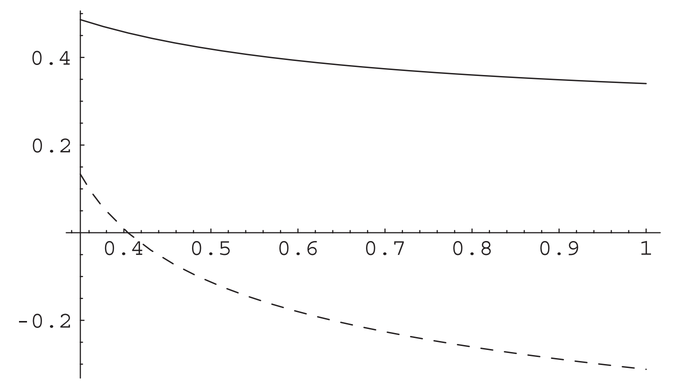


spacelike $q^2 < 0$; $q'^2 = 0$ **vs** **timelike** $q^2 = 0$; $q'^2 > 0$

$e\ N \to\ e'\ N\ \gamma$ **vs** $\gamma\ N \to\ N\ \mu^+\ \mu^-$

LO : $\mathcal{A}_{DVCS} = \mathcal{A}^*_{TCS}$

$$R^q_{T-S} = \frac{C^q_{1(\mathrm{TCS})} - C^{q*}_{1(\mathrm{DVCS})}}{C^q_0}.$$



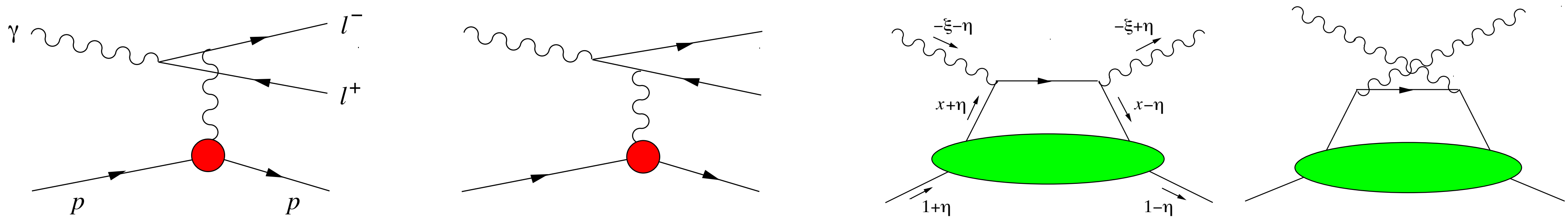
NLO : $\mathcal{A}_{DVCS} \neq \mathcal{A}^*_{TCS}$

➩ **Both timelike and spacelike data useful to check NLO analysis !**

GPDs at LHC (and RHIC)

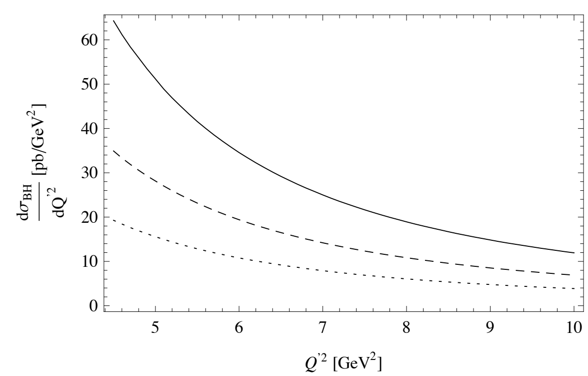
➪ Ultraperipheral Collisions : quasi real photons from proton beam

$\mu^+\mu^-$ pair production



QED dominates over TCS but in specific kinematics

$\rightarrow$ cutting out QED with angular cuts :

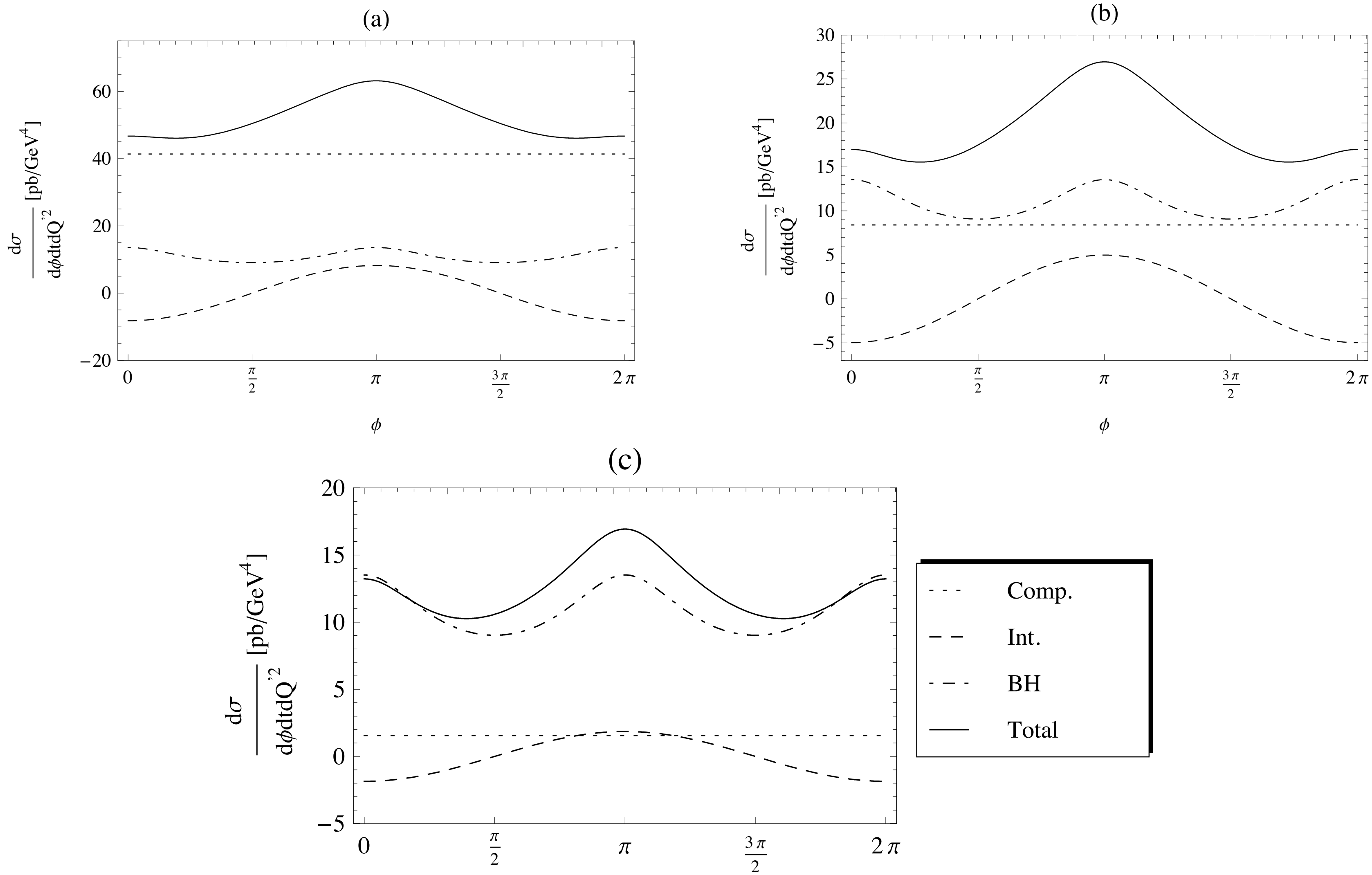


GPDs are expected to be large at small $x \approx \xi$ $\xi \approx Q^2/s_{\gamma p}$

➪ Probe of sea and gluon GPDs in small x regime

Observing TCS at LHC

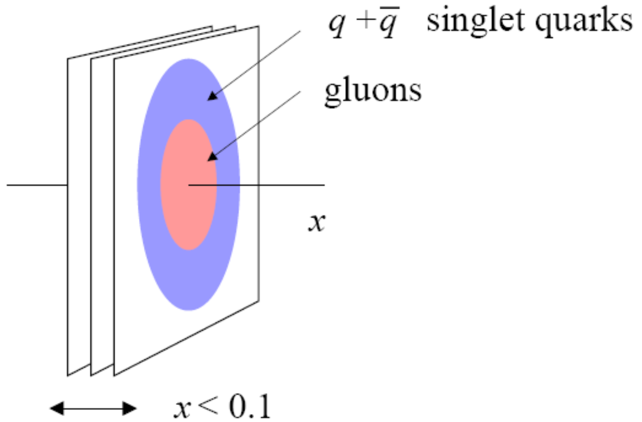
➪ **Characteristic signal from interference** (charge conj. odd)

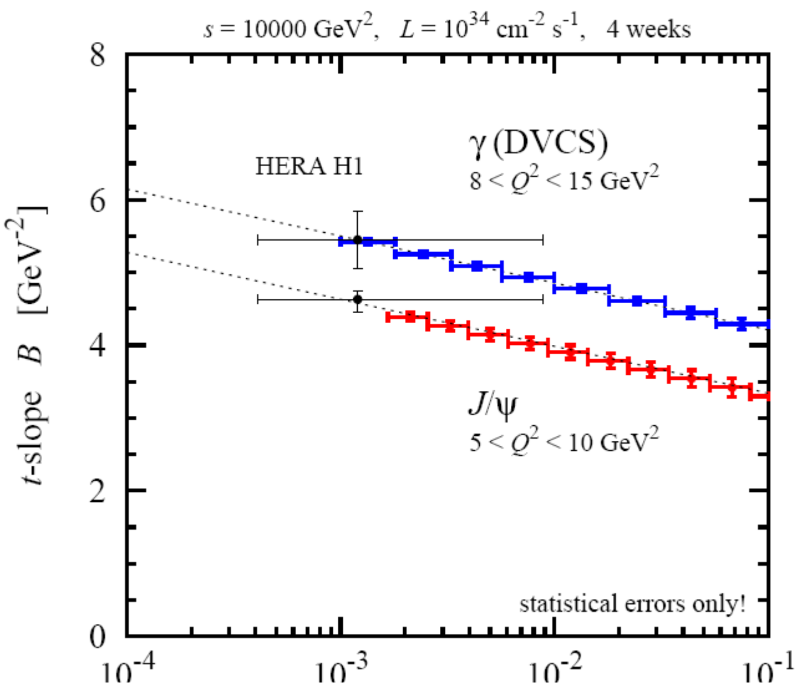


$s_{\gamma p} = 10^7\ GeV^2$ $\quad$ $s_{\gamma p} = 10^5\ GeV^2$ $\quad$ $s_{\gamma p} = 10^3\ GeV^2$ $\quad$ $Q'^2 = 5\ GeV^2$

Gluon imaging through DVCS

from T Horn, EIC study





- Do singlet quarks and gluons have the same transverse distribution?
  - Hints from HERA: $Area(q+\bar{q}) > Area(g)$
  - Dynamical models predict difference: pion cloud, constituent quark picture *[Strikman, Weiss 09]*
  - No difference assumed in present pp MC generators for LHC!

- EIC: gluon size from J/ψ , singlet quark size from DVCS
  - x-dependence: quark vs. gluon diffusion in wave function
  - Detailed analysis: LO $\rightarrow$ NLO *[Mueller et al.]*

Detailed differential image of nucleon's partonic structure

Exclusive Meson production and GPDs

Vector meson production the most dominant process

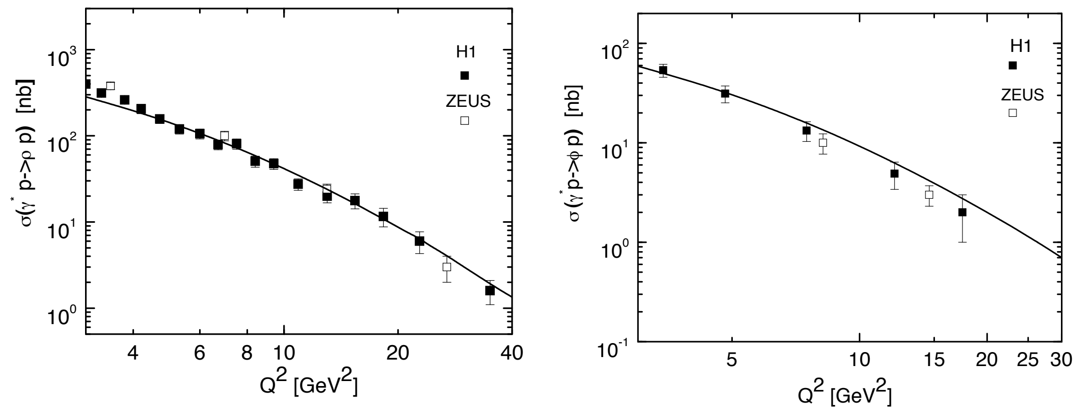


Figure 5: The integrated cross section for $\gamma^* p \to \rho p$ (left) and $\gamma^* p \to \phi p$ (right) versus Q^2 at $W \simeq 75$ GeV. Data taken from [12, 44] (filled squares) and [13, 45] (open squares) for ρ and ϕ production, respectively. The solid lines represent our results.

Goloskokov Kroll hep-ph/0501242

ρ_L **production leading twist and dominant.**

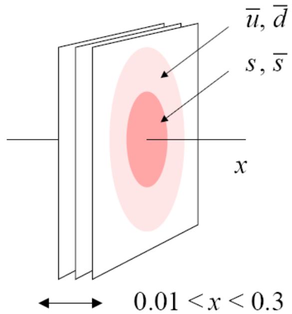
ρ^0_L **production mostly sensitive to gluon GPDs**

probes $H(x, \xi, t)$ **and** $E(x, \xi, t)$ **GPDs**

Sea quark imaging through π electroproduction

from T Horn, EIC study

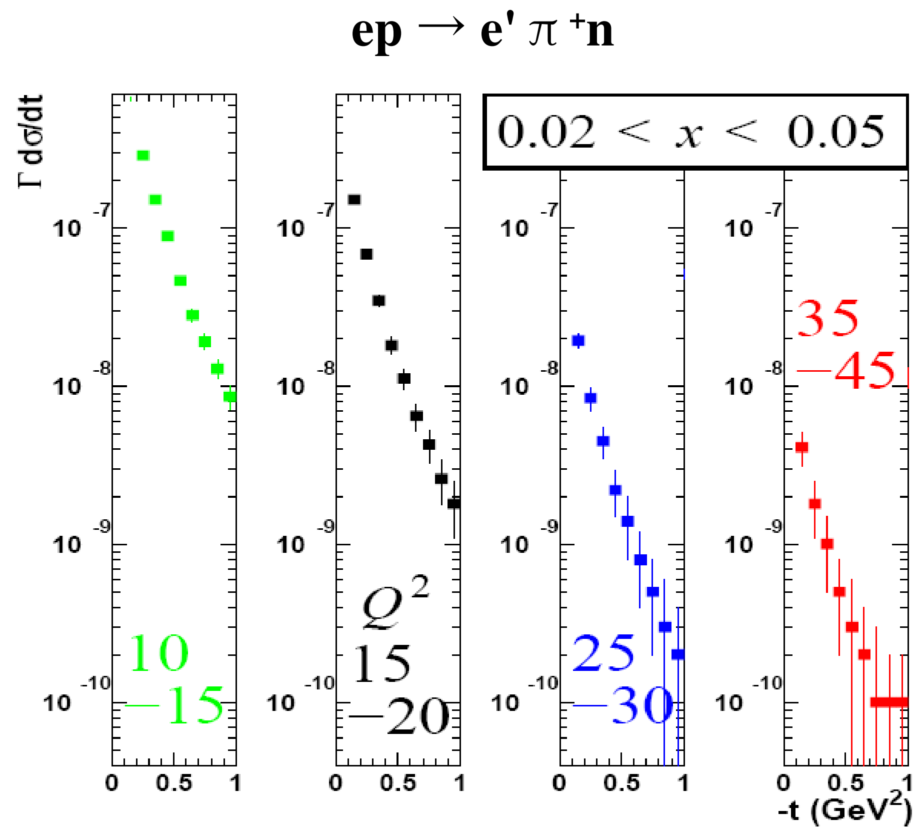
- New territory for collider!



- Spatial structure of *non-perturbative sea*
  - Closely related to JLab 12 GeV
    - Quark spin/flavor separations
    - Nucleon/meson structure

- Simulation for π^+ production assuming 100 days at a luminosity of 10^{34} with 5 on 50 GeV (s=1000 GeV^2)
  - V. Guzey, C. Weiss: Regge model
  - T. Horn: empirical π^+ parameterization

- Lower and more symmetric energies essential



[Tanja Horn, Antje Bruell, Christian Weiss]

Transverse spatial structure of non-perturbative sea quarks!

Spin dependent GPDs

A virtue of exclusive processes

$\rightarrow$ spin physics without polarized beam/target !

π or η production (twist 2) : sensitive to $\tilde{H}(x,\xi,t)$ and $\tilde{E}(x,\xi,t)$ GPDs

recall : $\tilde{H}^q(x,0,0) = \Delta^q(x); \tilde{H}^g(x,0,0) = x\Delta^G(x)$

because γ^5 in meson DA selects γ^5 in GPD operator

Vector meson production selects "helicity averaged" GPDs ;

Photon (DVCS or TCS) production mixes all 4 chiral even GPDs

What about chiral - odd GPDs ?

Transversity GPDs

Transverse spin structure is very badly known !

$\Rightarrow$ Even at the PDF level ($\Delta_T q(x)$) :
interesting but indirect (through TMDs) measurement of transversity
$\Rightarrow$ Usefulness of direct measurements of chiral-odd GPDs.

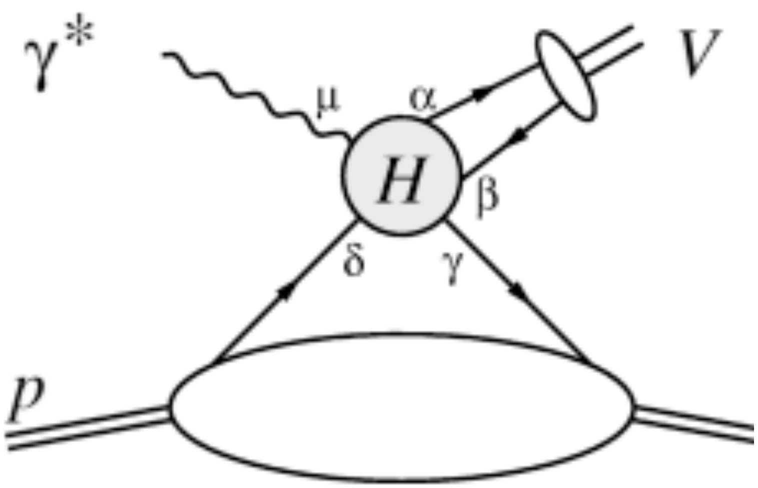
4 leading twist C-O GPDs : $H_T^q(x,\xi,t),\ E_T^q(x,\xi,t),\ \tilde{H}_T^q(x,\xi,t),\ \tilde{E}_T^q(x,\xi,t)$

with $H_T^q(x,0,0) = \Delta_T q(x)$.

Access to more features about the spin nucleon structure as :

- Momentum correlations of transversally polarized partons in a transversally polarized nucleon
- Transverse asymmetry of the angular momentum carried by quarks
- Density of polarized quarks in the impact parameter plane

Exclusive electroproduction of one vector meson $V_T = \rho_T$



Diehl, Gousset, BP, Phys. Rev. D59, 034023
Collins and Diehl, Phys. Rev. D61, 114015

DA of $V_T \propto < 0|\bar{u}(0)\sigma^{\alpha\beta}u(x)|V >$

C-O GPDs $\propto < p'|\bar{u}(0)\sigma^{\delta\gamma}u(x)|p >$

Basic Idea : C-O nature of ρ_T DA reveals the C-O GPDs

BUT due to angular momentum and chirality conservation

$$Tr[H^{\mu}_{\alpha\beta\gamma\delta}\sigma^{\alpha\beta}\sigma^{\delta\gamma}] = 0$$

at leading power in $1/Q$ to all orders in the strong coupling

way out $\rightarrow$ twist 3 contributions to π electroproduction ...or ...

Photo- or electroproduction of 2 vector mesons

Ivanov, BP, Szymanowski and Teryaev, Phys. Lett. B550, 65
Enberg, BP and Szymanowski, Eur. Phys. J. C47, 87

Process at high energy, governed by the virtuality of the Pomeron

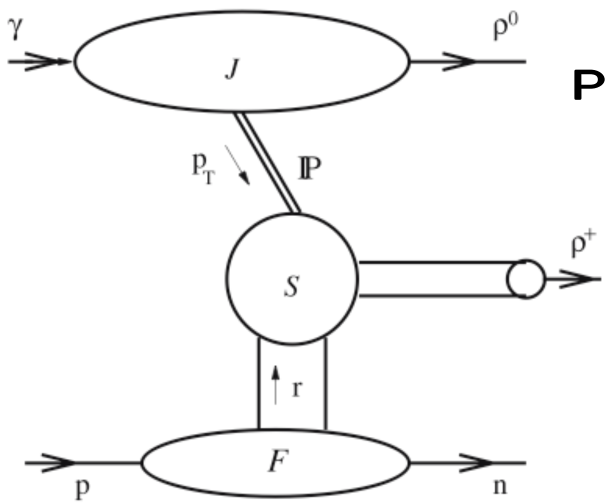


Photo- or electroproduction on a (polarized) nucleon target

Mesons (ρ^0_L and ρ^+_T) separated by a large rapidity gap

Hard scale = virtuality of the Pomeron (or p_T of the ρ^0)

Estimate of rate and access to H_T in the ERBL domain

An hybrid description of exclusive processes

mixing k_T factorization (à la BFKL) and colinear factorization.

Modeling Chiral-Odd GPDs

model for GPD based on tensor meson exchange :

$$H_T^{ud}(x,\xi,0) = \frac{g_{b_1 NN} f_{b_1}^T \langle k_\perp^2 \rangle}{2\sqrt{2} M_N\, m_{b_1}^2} \, \frac{\phi_\perp^{b_1}\left(\frac{x+\xi}{2\xi}\right)}{2\xi}$$

+ some existing first Lattice QCD calculations

$\rightarrow$ Born amplitude through $\gamma \rightarrow \rho^0$ Impact factor $J^{\gamma\rightarrow\rho^0}$:

$$\begin{aligned}\mathcal{M}^{\gamma\, p \rightarrow \rho^0\, \rho_T^+\, n} &= \sin\theta\, 16\pi^2 W^2 \alpha_s f_\rho^T \xi \sqrt{\frac{1-\xi}{1+\xi}} \frac{C_F}{N_c\,(p_T^2)^2} \\ &\times \int_0^1 \frac{du\ \phi_\perp(u)}{u^2 \bar{u}^2} J^{\gamma\rightarrow\rho^0}(up_T, \bar{u}p_T) \frac{H_T^{ud}(\xi(2u-1),\xi,t)}{\sqrt{2}}\end{aligned}$$

Nucleon spin orientation appears only through $sin(\theta)$

unpolarized cross section non-zero !

Estimated cross sections

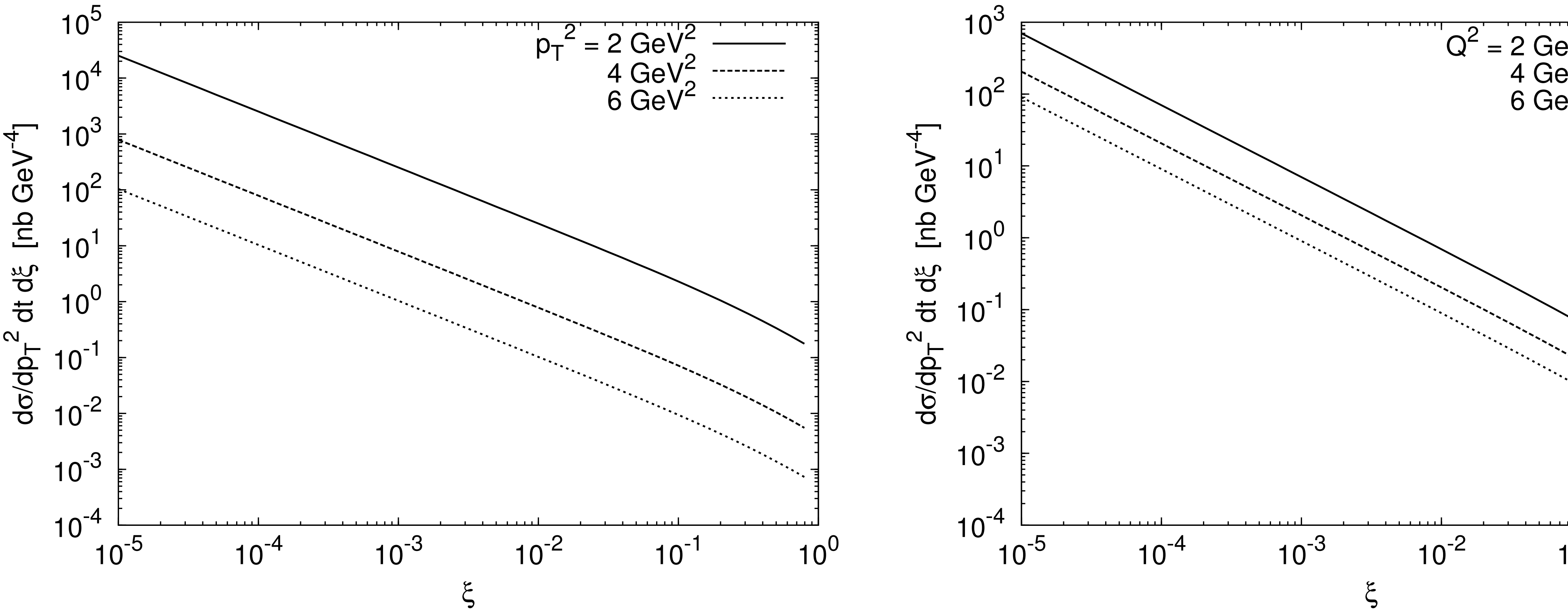


Figure 5.30: The differential cross section for the photoproduction (a) and electroproduction (b) of pair $\rho_T^0\,\rho_T^+$ as a function of ξ for (a) $p_T^2 = 2, 4$ and 6 GeV^2 and for (b) $p_T^2 = 2$ GeV^2 and $Q^2 =$ GeV^2. The cross sections for the production of the meson pair $\rho_T^0\,\rho_T^0$ are two times smaller.

Chiral-Odd GPDs should be measured at EIC / LHeC

Looking for the Odderon

(within k_T factorization - link to twist 3 gluon GPD ?)

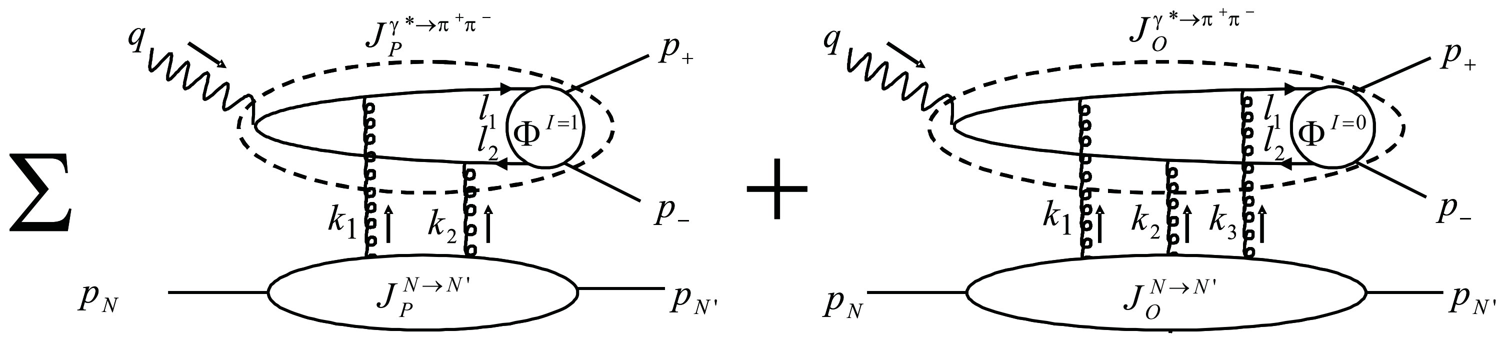


Figure 6.33: Feynman diagrams describing $\pi^+\pi^-$ electroproduction in the Born approximation.

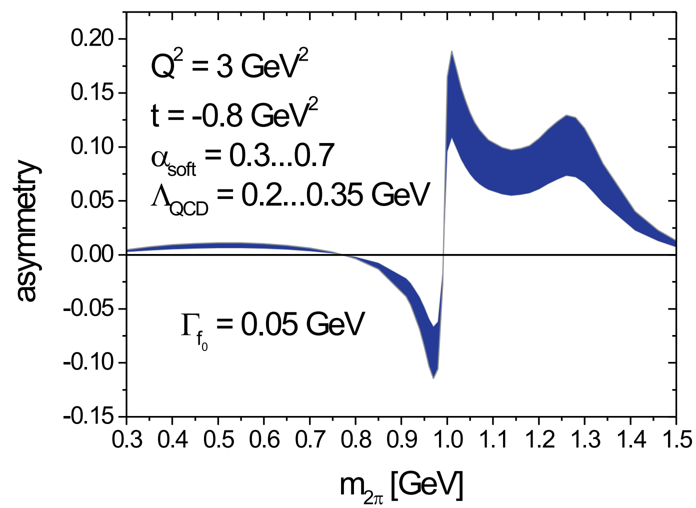


Figure 6.34: The charge asymmetry defined in Eq. (6.17) as a function of the $\pi^+\pi^-$ invariant mass $m_{2\pi}$.

$$A(Q^2, t, m_{2\pi}^2) = \frac{\int \cos\theta\, d\sigma(s, Q^2, t, m_{2\pi}^2, \theta)}{\int d\sigma(s, Q^2, t, m_{2\pi}^2, \theta)} = \frac{\int_{-1}^{1} \cos\theta\, d\cos\theta\, 2\ \mathrm{Re}\left[\mathcal{M}_P^{\gamma_L^*}(\mathcal{M}_O^{\gamma_L^*})^*\right]}{\int_{-1}^{1} d\cos\theta \left[|\mathcal{M}_P^{\gamma_L^*}|^2 + |\mathcal{M}_O^{\gamma_L^*}|^2\right]}$$

Conclusions

➪ The future of GPD measurements is bright at medium energies : JLab 12, COMPASS 2

➪ Much work began to uncover EIC possibilities in this domain.

➪ Much remains to be done for LHeC, including detector requirements.

NB : some uncovered items : nuclear GPDs, including coherent and break-up cases, saturation phenomena ...

Thank you