Results from Hall A on π^0 and photon electroproduction

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August 30^{th} 2017

Introduction

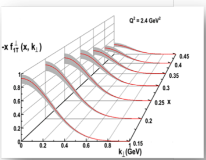
A lot have been already said in the previous days about experiment or theory for DVCS and DVMP (Raphael, Tanja, Silvia, Vladimir, Kresimir,...).

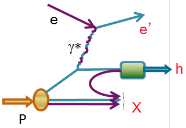
- This talk will include some reminders and skip a lot of introduction (Do not hesitate to stop me if something is missing).
- This talk was built according to the content and remarks from previous talk (so sorry if they are some discontinuities).
- This talk will focus on last results from Hall A for π^0 and photon electroproduction.
- I have some questions to ask you for next measurements.

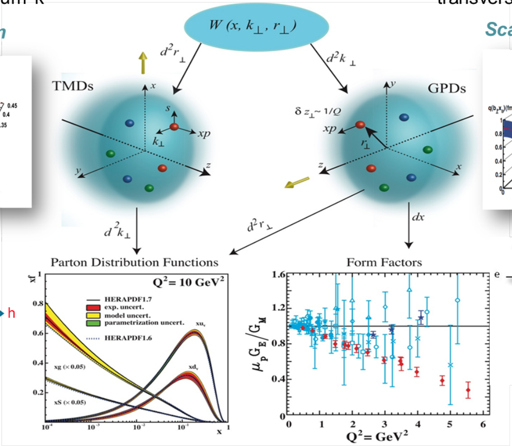
Nucleon structure and distributions

TMDs: Fraction of longitudinal momentum x et transverse momentum k

Scan in momentum

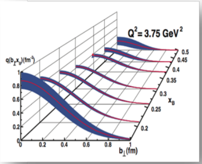


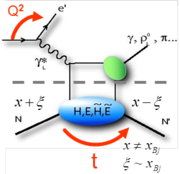




GPDs: Fraction of longitudinal momentum x et transverse position b

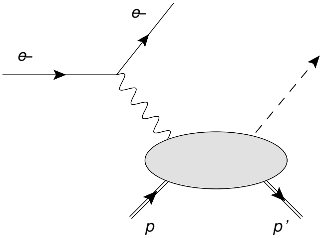
Scan in position





Deep exclusive processes

By measuring the cross section of deep exclusive processes, we get insights about the structure of the nucleon.

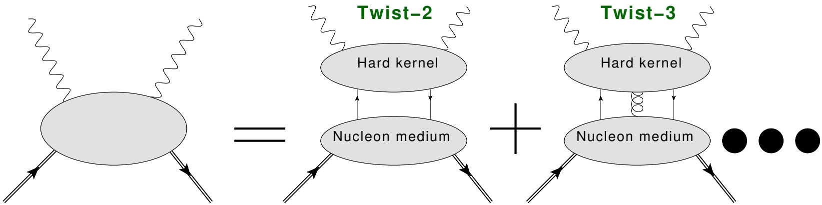


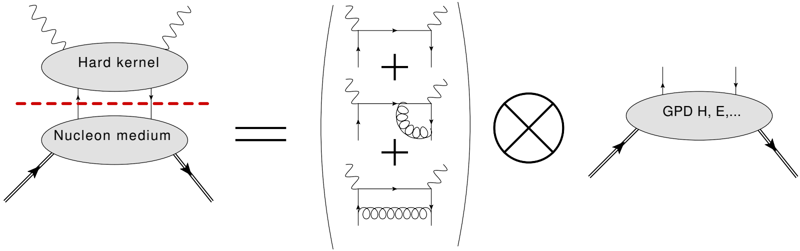
1. The electron interacts with the proton by exchanging a hard virtual photon (with polarization +,-,0).
2. The proton emits a particle (γ, π^0, ρ,...)

How to connect this amplitude to the generalized parton distributions?
The Factorization

We will first discuss $ep \rightarrow ep\gamma$ and then $ep \rightarrow ep\pi^0(\gamma\gamma)$.

Factorization and GPDs





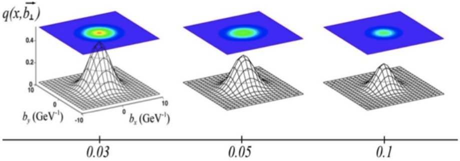
The amplitudes at twist-$(n+1)$ are suppressed by a factor $\frac{1}{Q}$ with respect to the twist-n amplitudes, with Q the virtuality of the photon.

The generalized parton distributions

At leading twist there are 8 GPDs for the proton:

- 4 chiral-even GPDs: H, E, $\widetilde{H}$ and $\widetilde{E}$.
- 4 chiral-odd GPDs: H_T, E_T, $\widetilde{H}_T$ and $\widetilde{E}_T$.

By Fourier transform of the GPD H, we obtain the distribution in the transverse plane of the partons as a function of their longitudinal momentum.

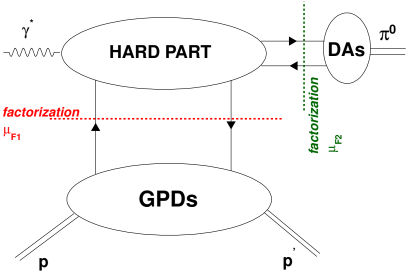


Keeping the correlation between longitudinal momentum and transverse spatial distribution of partons, we can study the total angular momentum of quarks.

π^0 electroproduction in the Hall A of Jefferson Laboratory

π^0 electroproduction and GPDs

In DVMP, there is an additional non-perturbative structure: the meson.



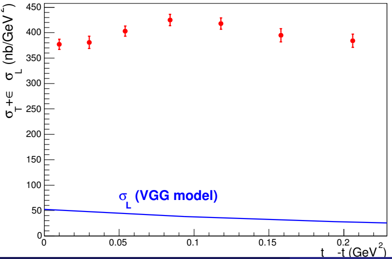
The amplitude is given by the product of two twist-expansions:
There is a coupling between the GPDs and the DAs.

$$\mathcal{M} = GPDs(x, \xi, t, \mu_{F1}) \otimes HARD(x/\xi, z, \mu_{F1}, \mu_{F2}) \otimes DA(z, \mu_{F2})$$

The unpolarized cross section can be written as the sum of responses according to the polarization of the virtual photon.

$$\frac{d^4\sigma}{dt\,d\phi\,dQ^2\,dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)\right],$$

Only the longitudinal response is leading-twist, involving $\widetilde{H}$ and $\widetilde{E}$.
Results from CLAS and Hall A are $\times 10$ higher than leading-twist predictions!



$Q^2 = 2.3$ GeV^2, $x_B = 0.36$
ϵ=0.651

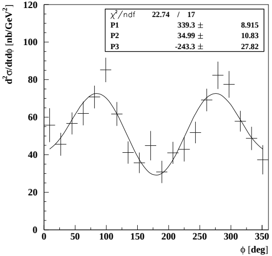
Fuchey E. *et al.* (Hall A collaboration), PhysRevC.83.025201 (2011)

What's going on?

$$\frac{d^4\sigma}{dtd\phi dQ^2 dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\left[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)\right],$$

Hints of a large transverse contribution:

- Asymmetries of π^+ from HERMES and L/T separation on π^+ (Hall C).
- Large amplitude of $\frac{d\sigma_{TT}}{dt}$ from CLAS and Hall A (ϕ-dependence).



$Q^2 = 1.75$ GeV^2, $x_B = 0.22$, t'=0.12 GeV^2
ϵ=0.457

I. Bedlinskiy *et al.* (CLAS collaboration), PhysRevC.90.025205 (2014)

Transversity GPDs and twist-3 DAs

At leading twist there are 8 GPDs:

- 4 chiral-even GPDs: H, E, $\widetilde{H}$ and $\widetilde{E}$.
- 4 chiral-odd GPDs: H_T, E_T, $\widetilde{H}_T$ and $\widetilde{E}_T$.

The twist-3 DAs are chiral-odd and might couple to transversity GPDs. Although $\frac{1}{Q}$-suppressed, twist-3 DAs are associated to a kinematical coefficient:

$$\mu_\pi = \frac{m_\pi^2}{m_u + m_d} \simeq 2.5 \text{ GeV}$$

which is higher than our Q-values.

Assuming the factorization for transversely polarized photon:

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)|\mathcal{H}_T|^2 - \frac{t'}{8m^2}|2\widetilde{\mathcal{H}}_T + \mathcal{E}_T|^2\right], \quad (1)$$

$$\frac{d\sigma_{TT}}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}|2\widetilde{\mathcal{H}}_T + \mathcal{E}_T|^2,$$

The first Rosenbluth separation of π^0 electroproduction

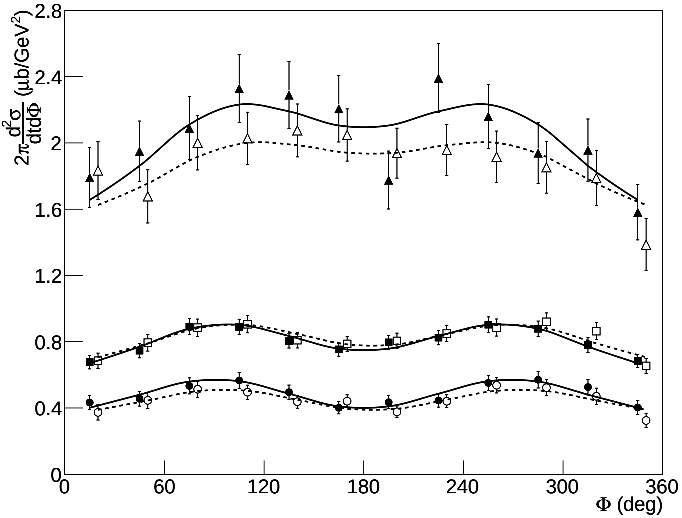
We need to separate σ_L and σ_T to confirm the large transverse contribution.

$$\frac{d^4\sigma}{dtd\phi dQ^2 dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\Big[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)\Big],$$

Setting	E (GeV)	Q^2 (GeV^2)	x_B	ϵ
2010-Kin1	(3.355 ; 5.55)	1.5	0.36	(0.52 ; 0.84)
2010-Kin2	(4.455 ; 5.55)	1.75	0.36	(0.65 ; 0.79)
2010-Kin3	(4.455 ; 5.55)	2	0.36	(0.53 ; 0.72)

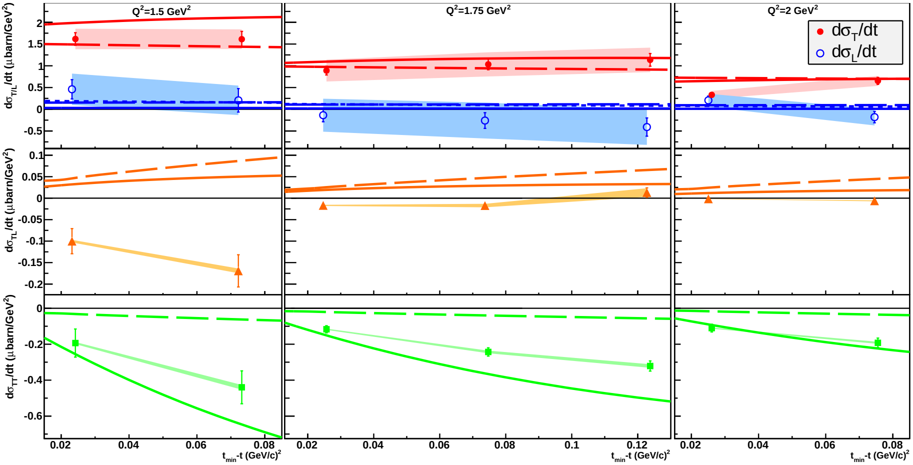
Rosenbluth separation: Measure $\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt}$ for two different ϵ-values at same Q^2, x_B and t'.

Results



- Q^2=1.5 GeV^2 Triangles
- Q^2=1.75 GeV^2 Squares
- Q^2=2 GeV^2 Circles

$\frac{\sigma_T}{dt}$ (red), $\frac{\sigma_L}{dt}$ (blue), $\frac{\sigma_{TL}}{dt}$ (orange) , $\frac{\sigma_{TT}}{dt}$ (green)



The Q-dependence is 9±2 for T, 4±2 for TT, 26±5 for TL.

NB: 3% normalization uncertainty has a dramatic effect for the separation.

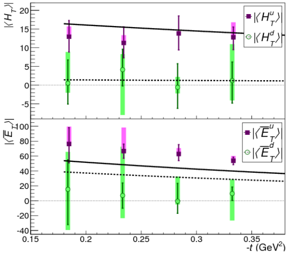
π^0 electroproduction off the neutron

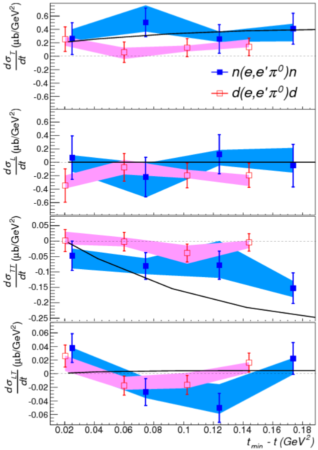
Data has been collected on Deuterium to study the neutron at Q^2=1.75 GeV^2.

Mazouz et al., PRL 118.222002, 2017

- As expected $_T$ is found to be the dominant contribution.
- Almost no coherent π^0 electroproduction.

Combining proton and neutron, let's try flavor separation.



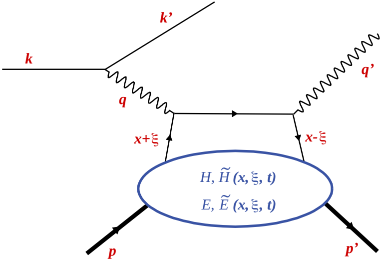


Conclusion about π^0 electroproduction

- π^0 electroproduction is a beautiful example of process for which the dominant contribution is not the leading-twist contribution.
- Offer exciting opportunity to access transversity GPDs (if factorization holds for transversely polarized photons).
- Good example of systematic uncertainties affecting differently the different harmonics of a cross section.
- Large lever arm in ϵ and L/T$\tilde{1}$ are the key for a successful (full of information) measurement of π^0 electroproduction.

Photon electroproduction in the Hall A of Jefferson Laboratory

DVCS and GPDs



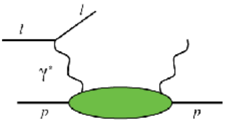
- $Q^2 = -q^2 = -(k - k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$
- x longitudinal momentum fraction carried by the active quark.
- $\xi \sim \frac{x_B}{2-x_B}$ the longitudinal momentum transfer.
- $t = (p - p')^2$ squared momentum transfer to the nucleon.

The GPDs enter the DVCS amplitude through a complex integral. This integral is called a *Compton form factor* (CFF).

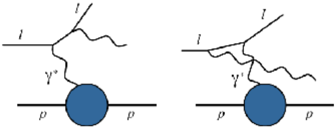
$$\mathcal{H}(\xi, t) = \int_{-1}^{1} H(x, \xi, t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) dx \, .$$

Photon electroproduction and GPDs

Experimentally we measure the cross section of the process $ep \to ep\gamma$.



DVCS

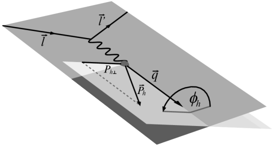


Bethe-Heitler

$$\frac{d^4\sigma(\lambda, \pm e)}{dQ^2 dx_B dt d\phi} = \frac{d^2\sigma_0}{dQ^2 dx_B} \frac{2\pi}{e^6} \times \left[\left| \mathcal{T}^{BH} \right|^2 + \left| \mathcal{T}^{DVCS} \right|^2 \mp \mathcal{I} \right] ,$$

with λ the helicity of the electron.

A parameterization of cross section



We can partially unfold the contributions, studying the ϕ-dependence.

$$|\mathcal{T}^{BH}|^2 = \frac{e^6 \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)}{x_B^2 t y^2 (1+\epsilon^2)^2 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi)} \quad \leftarrow \text{KNOWN!}$$

$$\left|\mathcal{T}^{DVCS}\right|^2 = \frac{e^6}{y^2 Q^2}\left\{c_0^{DVCS} + \sum_{n=1}^{2}\left[c_n^{DVCS}\cos(n\phi) + \lambda s_1^{DVCS}\sin(n\phi)\right]\right\}$$

$$\mathcal{I} = \frac{e^6}{x_B y^3 \mathcal{P}_1(\phi)\mathcal{P}_2(\phi) t}\left\{c_0^{\mathcal{I}} + \sum_{n=1}^{3}\left[c_n^{\mathcal{I}}\cos(n\phi) + \lambda s_n^{\mathcal{I}}\sin(n\phi)\right]\right\}$$

A parameterization of cross section

The CFFs are encapsulated in c_n and s_n, offering a parameterization of the cross section. In the leading twist approximation for unpolarized target:

$$
\begin{aligned}
c_0^{DVCS} \propto \quad & \mathcal{C}^{DVCS}(\mathcal{F}, \mathcal{F}^*) = 4(1 - x_B)\mathcal{H}\mathcal{H}^* + \cdots \qquad (2) \\
c_1^{\mathcal{I}} \propto \quad & Re\ \mathcal{C}^{\mathcal{I}}(\mathcal{F}) = F_1\ Re\mathcal{H} + \xi(F_1 + F_2)\ Re\widetilde{\mathcal{H}} - \frac{t}{4M^2} F_2\ Re\mathcal{E}\,, \\
s_1^{\mathcal{I}} \propto \quad & Im\ \mathcal{C}^{\mathcal{I}}(\mathcal{F}) = F_1\ Im\mathcal{H} + \xi(F_1 + F_2)\ Im\widetilde{\mathcal{H}} - \frac{t}{4M^2} F_2\ Im\mathcal{E}\,,
\end{aligned}
$$

By studying the ϕ-dependence of the observables, we can extract the CFFs. However there are too many CFFs to extract them all... We have to make some assumptions.

Mueller D., Belitsky A.V., Phys.Rev.D.82 (2010)

A first experiment in the Hall A in 2004

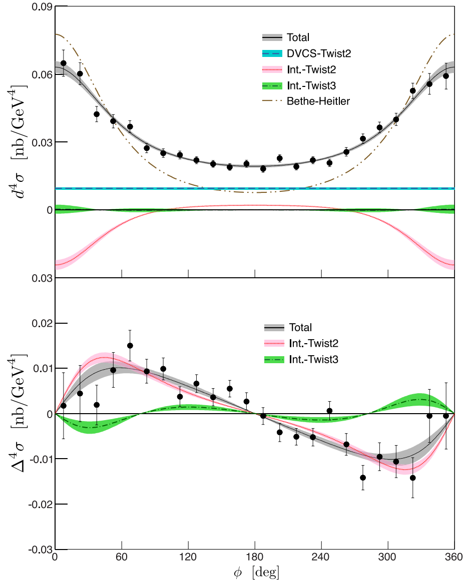
At leading twist, the cross section should be mostly given by $\mathcal{C}^{DVCS}(\mathcal{F}, \mathcal{F}^*)$ ($\cos 0\phi$), *Re* $\mathcal{C}^{\mathcal{I}}(\mathcal{F})$ ($\cos\phi$) and *Im* $\mathcal{C}^{\mathcal{I}}(\mathcal{F})$ ($\sin\phi$) (considered all independent).

If there is mainly leading-twist at JLab, we can measure them and see if they are Q^2-independent.

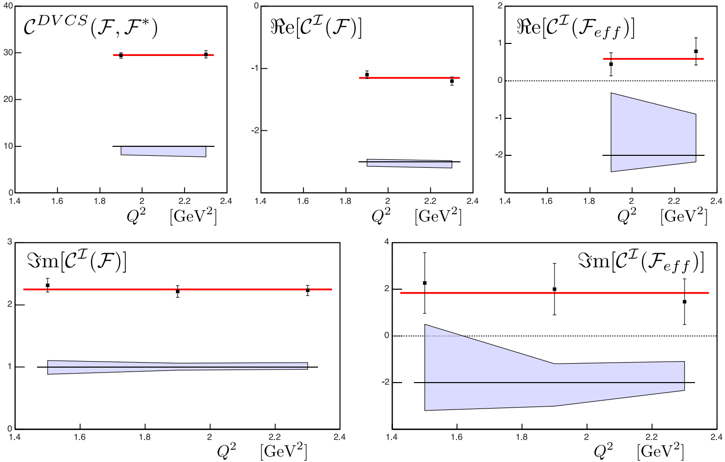
Setting	E (GeV)	Q^2 (GeV^2)	x_B	W (GeV)
2004-Kin1	5.7572	1.5	0.36	1.9
2004-Kin2	5.7572	1.9	0.36	2.06
2004-Kin3	5.7572	2.3	0.36	2.23

NB: In the paper of 2006, $DVCS^2$ was neglected and only CFFs from interference were kept. The ϕ-modelated uncertainty showed by Kresimir on Monday is the uncertainty related to the choice of parameterization.

Cross section and effective CFFs extraction



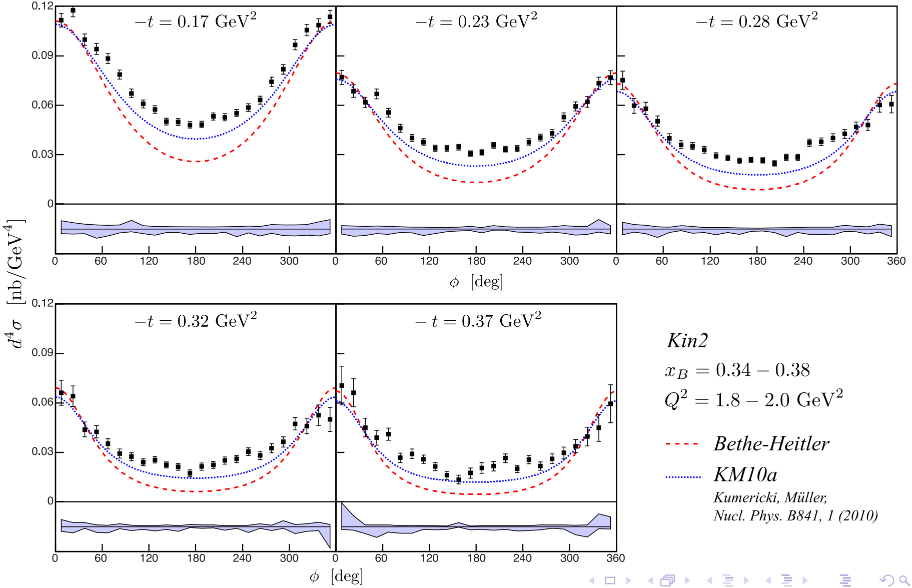
About the scaling...



People were somewhat happy of this conclusion, but:

- All parameters are considered independent but it is not...
- And there is Vladimir's work.

Here are the cross sections results!



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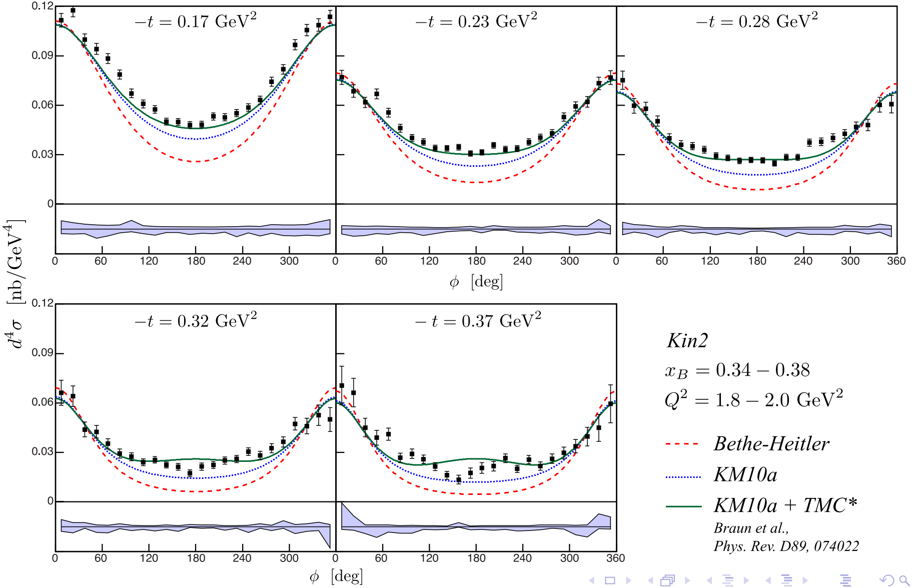
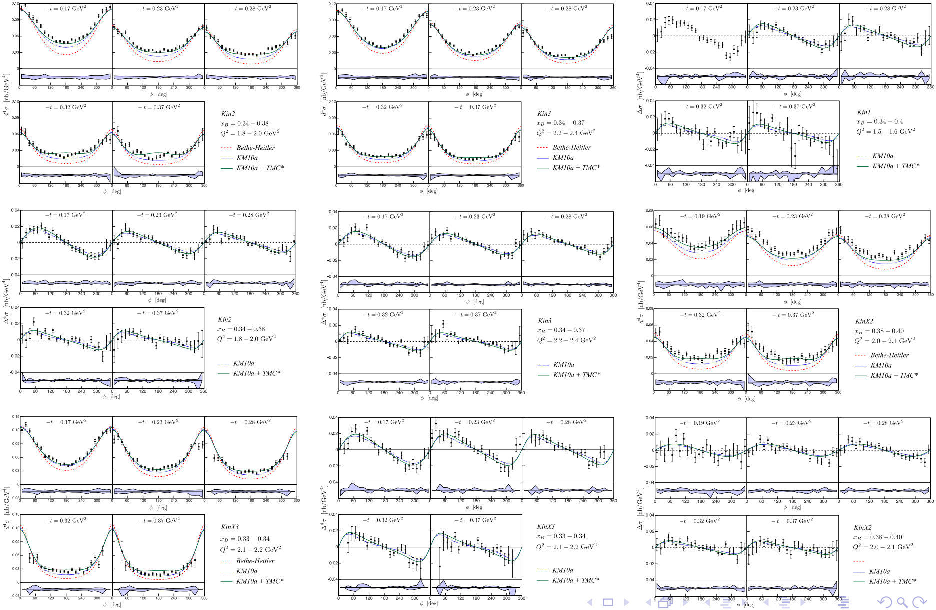


A lot of new DVCS data



Rosenbluth separation

The ϕ-dependence is not enough to disentangle the contributions (We neglected terms). Using the beam energy dependence, we can add constrains on the model (separation of DVCS and interference contribution)

Setting	E (GeV)	Q^2 (GeV^2)	x_B	W (GeV)
2004-Kin1	5.7572	1.5	0.36	1.9
2004-Kin2	5.7572	1.9	0.36	2.06
2004-Kin3	5.7572	2.3	0.36	2.23

Setting	E (GeV)	Q^2 (GeV^2)	x_B	W (GeV)
2010-Kin1	(3.355 ; 5.55)	1.5	0.36	1.9
2010-Kin2	(4.455 ; 5.55)	1.75	0.36	2
2010-Kin3	(4.455 ; 5.55)	2	0.36	2.1

But, before, let's take a closer look to the kinematical power corrections.

Where do the kinematical power corrections come from?

Belitsky, Muller and Ji decomposed the DVCS amplitude in helicity amplitude, using the lab frame as reference frame. In the BMJ formalism, the cross section is parametrized by a set of CFFs:

$$\mathcal{F}_{\mu\nu} \in \left\{\mathcal{H}_{\mu\nu}, \mathcal{E}_{\mu\nu}, \tilde{\mathcal{H}}_{\mu\nu}, \tilde{\mathcal{E}}_{\mu\nu}\right\} \tag{3}$$

where μ (ν) is the helicity of the virtual (real) photon. Therefore we can distinguish three cases:

- $\mathcal{F}_{++}$ are the *helicity-conserved CFFs*. They are the regular leading-twist CFFs which describes diagram for which virtual and real photon have the same helicity.
- $\mathcal{F}_{0+}$ are the *longitudinal-to-transverse helicity flip CFFs*. They are *twist-3* CFFs related to the contribution of the longitudinal polarization of the virtual photon.
- $\mathcal{F}_{-+}$ are the *transverse-to-transverse helicity flip CFFs*. At leading-order, these CFFs are *twist-4*. But at NLO order, these CFFs involves the *twist-2* gluon transversity GPDs.

Where do the kinematical power corrections come from?

In the BMP formalism, the reference frame is taken such as both photons have purely longitudinal momentum. This choice makes easier the inclusion of kinematically suppressed terms (in t/Q^2 or M^2/Q^2). In the BMP formalism, the cross section is parametrized by a set of CFFs:

$$\mathbb{F}_{\mu\nu} \in \left\{ \mathbb{H}_{\mu\nu}, \mathbb{E}_{\mu\nu}, \tilde{\mathbb{H}}_{\mu\nu}, \tilde{\mathbb{E}}_{\mu\nu} \right\} \tag{4}$$

where μ (ν) is the helicity of the virtual (real) photon. Therefore we can distinguish three cases:

- $\mathbb{F}_{++}$ are the *helicity-conserved CFFs*. They are twist-2 CFFs.
- $\mathbb{F}_{0+}$ are the *longitudinal-to-transverse helicity flip CFFs*. They are *twist-3* CFFs.
- $\mathbb{F}_{-+}$ are the *transverse-to-transverse helicity flip CFFs*. At LO, these CFFs are *twist-4*. At NLO, these CFFs involves the gluon transversity GPDs.

BMP... BMJ... which difference?

But let's stay at leading-order. The BMP CFFs are not the same as the BMJ CFFs. The BMP CFFs are more complex terms. As an example, $\mathbb{H}_{++}$, we have:

$$\mathcal{H}_{++} = T_0 \otimes H \; , \tag{5}$$

$$\mathbb{H}_{++} = T_0 \otimes H + \frac{-t}{Q^2}\left[\frac{1}{2}T_0 - T_1 - 2\xi D_\xi T_2\right] \otimes H + \frac{2t}{Q^2}\xi^2 \partial_\xi T_2 \otimes (H+E) \; . \tag{6}$$

We can go from BMP to BMJ CFFs by making the following replacement:

$$\mathcal{F}_{++} = \mathbb{F}_{++} + \frac{\chi}{2}\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] - \chi_0 \mathbb{F}_{0+} \; , \tag{7}$$

$$\mathcal{F}_{-+} = \mathbb{F}_{-+} + \frac{\chi}{2}\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] - \chi_0 \mathbb{F}_{0+} \; , \tag{8}$$

$$\mathcal{F}_{0+} = -(1+\chi)\mathbb{F}_{0+} + \chi_0\left[\mathbb{F}_{++} + \mathbb{F}_{-+}\right] \; , \tag{9}$$

with: $\chi_0 \propto \sqrt{t'}/Q$ and $\chi \propto t'/Q^2$. The leading-twist assumption gives different results between BMP and BMJ.

Differences in the LT-LO assumption: BMJ

Assuming leading-twist and LO in BMJ, we have $\mathcal{F}_{-+} = 0$ and $\mathcal{F}_{0+} = 0$. It is important when regarding the DVCS amplitude. We have:

$$c_{0,\mathrm{unp}}^{\mathrm{VCS}} = 2\frac{2-2y+y^2+\frac{\epsilon^2}{2}y^2}{1+\epsilon^2}\,\mathcal{C}_{\mathrm{unp}}^{\mathrm{VCS}}(\mathcal{F}_{\pm+},\mathcal{F}_{\pm+}^*) + 8\frac{1-y-\frac{\epsilon^2}{4}y^2}{1+\epsilon^2}\,\mathcal{C}_{\mathrm{unp}}^{\mathrm{VCS}}(\mathcal{F}_{0+},\mathcal{F}_{0+}^*)\,, \tag{10}$$

$$\left\{\begin{array}{c} c_{1,\mathrm{unp}}^{\mathrm{VCS}} \\ s_{1,\mathrm{unp}}^{\mathrm{VCS}} \end{array}\right\} = \frac{4\sqrt{2}\sqrt{1-y-\frac{\epsilon^2}{4}y^2}}{1+\epsilon^2}\left\{\begin{array}{c} 2-y \\ -\lambda y\sqrt{1+\epsilon^2} \end{array}\right\}\left\{\begin{array}{c} \Re\mathrm{e} \\ \Im\mathrm{m} \end{array}\right\}\mathcal{C}_{\mathrm{unp}}^{\mathrm{VCS}}\left(\mathcal{F}_{0+}\middle|\mathcal{F}_{++}^*,\mathcal{F}_{-+}^*\right), \tag{11}$$

$$c_{2,\mathrm{unp}}^{\mathrm{VCS}} = 8\frac{1-y-\frac{\epsilon^2}{4}y^2}{1+\epsilon^2}\,\Re\mathrm{e}\,\mathcal{C}_{\mathrm{unp}}^{\mathrm{VCS}}\left(\mathcal{F}_{-+},\mathcal{F}_{++}^*\right). \tag{12}$$

which reduces to:

$$c_{0,\mathrm{unp}}^{\mathrm{VCS}} = 2\frac{2-2y+y^2+\frac{\epsilon^2}{2}y^2}{1+\epsilon^2}\,\mathcal{C}_{\mathrm{unp}}^{\mathrm{VCS}}(\mathcal{F}_{++},\mathcal{F}_{++}^*) \tag{13}$$

The DVCS amplitude is ϕ-**independent** with a **single** beam-energy dependence.

Differences in the LT-LO assumption: BMP

Assuming leading-twist and LO in BMP, we have $\mathbb{F}_{-+} = 0$ and $\mathbb{F}_{0+} = 0$.

$$\mathcal{F}_{++} = \left(1 + \frac{\chi}{2}\right) \mathbb{F}_{++} \,, \quad (14)$$

$$\mathcal{F}_{-+} = \frac{\chi}{2} \mathbb{F}_{++} \,, \quad (15)$$

$$\mathcal{F}_{0+} = \chi_0 \mathbb{F}_{++} \,, \quad (16)$$

It is important when regarding the DVCS amplitude.

$$c_{0,\mathrm{unp}}^{\mathrm{VCS}} = 2 \frac{2 - 2y + y^2 + \frac{\epsilon^2}{2} y^2}{1 + \epsilon^2} \mathcal{C}_{\mathrm{unp}}^{\mathrm{VCS}}(\mathcal{F}_{\pm+}, \mathcal{F}_{\pm+}^*) + 8 \frac{1 - y - \frac{\epsilon^2}{4} y^2}{1 + \epsilon^2} \mathcal{C}_{\mathrm{unp}}^{\mathrm{VCS}}(\mathcal{F}_{0+}, \mathcal{F}_{0+}^*) \,, \quad (17)$$

$$\left\{ \begin{array}{c} c_{1,\mathrm{unp}}^{\mathrm{VCS}} \\ s_{1,\mathrm{unp}}^{\mathrm{VCS}} \end{array} \right\} = \frac{4\sqrt{2}\sqrt{1 - y - \frac{\epsilon^2}{4} y^2}}{1 + \epsilon^2} \left\{ \begin{array}{c} 2 - y \\ -\lambda y \sqrt{1 + \epsilon^2} \end{array} \right\} \left\{ \begin{array}{c} \Re\mathrm{e} \\ \Im\mathrm{m} \end{array} \right\} \mathcal{C}_{\mathrm{unp}}^{\mathrm{VCS}} \left(\mathcal{F}_{0+} \middle| \mathcal{F}_{++}^*, \mathcal{F}_{-+}^*\right) , \quad (18)$$

$$c_{2,\mathrm{unp}}^{\mathrm{VCS}} = 8 \frac{1 - y - \frac{\epsilon^2}{4} y^2}{1 + \epsilon^2} \Re\mathrm{e}\, \mathcal{C}_{\mathrm{unp}}^{\mathrm{VCS}} \left(\mathcal{F}_{-+}, \mathcal{F}_{++}^*\right) . \quad (19)$$

The DVCS amplitude is **no longer** ϕ-independent with **multiple** beam-energy dependences.

Differences in the LT-LO assumption: BMP

Assuming leading-twist and LO in BMP, we have $\mathbb{F}_{-+} = 0$ and $\mathbb{F}_{0+} = 0$.

$$\mathcal{F}_{++} = \left(1 + \frac{\chi}{2}\right) \mathbb{F}_{++} \,, \tag{20}$$

$$\mathcal{F}_{-+} = \frac{\chi}{2}\mathbb{F}_{++} \,, \tag{21}$$

$$\mathcal{F}_{0+} = \chi_0 \mathbb{F}_{++} \,, \tag{22}$$

It is important when regarding the DVCS amplitude. With $\mathcal{C}^{\mathrm{VCS}}_{\mathrm{unp}}\left(\mathbb{F}_{++}, \mathbb{F}^*_{++}\right)$ in factor,

$$c^{\mathrm{VCS}}_{0,\mathrm{unp}} = 2\frac{2 - 2y + y^2 + \frac{\epsilon^2}{2}y^2}{1+\epsilon^2}\left(\left(1 + \frac{\chi}{2}\right)^2 + \left(\frac{\chi}{2}\right)^2\right) + 8\frac{1 - y - \frac{\epsilon^2}{4}y^2}{1+\epsilon^2}(\chi_0)^2 \,, \tag{23}$$

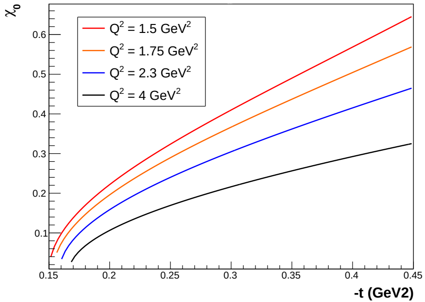
$$c^{\mathrm{VCS}}_{1,\mathrm{unp}} = \left(1 + \frac{\chi}{2}\right)\left(\chi_0 + \frac{\chi}{2}\right)\frac{4\sqrt{2}\sqrt{1 - y - \frac{\epsilon^2}{4}y^2}}{1+\epsilon^2}(2-y) \,, \tag{24}$$

$$c^{\mathrm{VCS}}_{2,\mathrm{unp}} = 8\frac{1 - y - \frac{\epsilon^2}{4}y^2}{1+\epsilon^2}\left(1 + \frac{\chi}{2}\right)\frac{\chi}{2} \,. \tag{25}$$

The DVCS amplitude is **no longer** ϕ-independent with **multiple** beam-energy dependences.

A complicated Rosenbluth separation

By changing the beam energy, we also change the polarization of the virtual photon.



We must take them into account. Let's fit the real and imaginary parts of $\mathbb{H}_{++}\mathbb{E}_{++}\tilde{\mathbb{H}}_{++}\tilde{\mathbb{E}}_{++}$:

- simultaneously on unpolarized and polarized cross sections,
- simultaneously on the two beam energies,
- simultaneously for the three Q^2-values (but I neglect the Q-evolution),

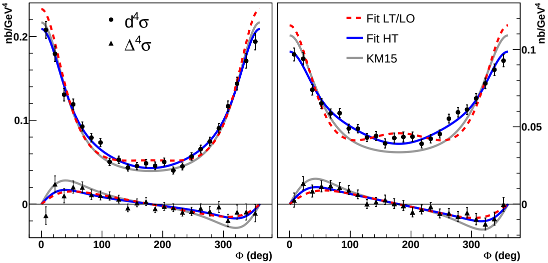


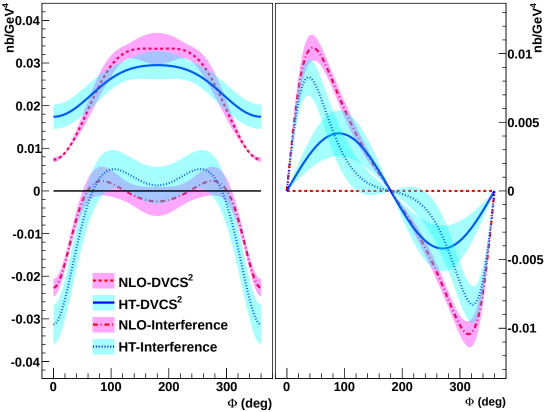
Figure: Q^2=1.75 GeV^2, -t=0.3 GeV^2. E=4.445 GeV (left) and E=5.55 GeV (right)

- LT/LO: $\mathbb{H}_{++}, \mathbb{E}_{++}, \tilde{\mathbb{H}}_{++}, \tilde{\mathbb{E}}_{++}$.
- HT: $\mathbb{H}_{++}, \tilde{\mathbb{H}}_{++}, \mathbb{H}_{0+}, \tilde{\mathbb{H}}_{0+}$.
- NLO: $\mathbb{H}_{++}, \tilde{\mathbb{H}}_{++}, \mathbb{H}_{-+}, \tilde{\mathbb{H}}_{-+}$.

Equally good fit between the HT and NLO scenario. M. Defurne *et al.*, Hall A collaboration, arXiv:1703.0944 (Accepted in Nat. Commun.)

Separation of DVCS and interference

Despite an equally good fit, slight differences appear when separating the interference and DVCS term.



In the HT scenario, the beam helicity dependent cross section is not a pure interference term, as it is usually assumed in most phenomenological analyses. M. Defurne *et al.*, Hall A collaboration, arXiv:1703.0944 (Accepted in Nat.

Conclusion on photon electroproduction from 6 GeV era in Hall A

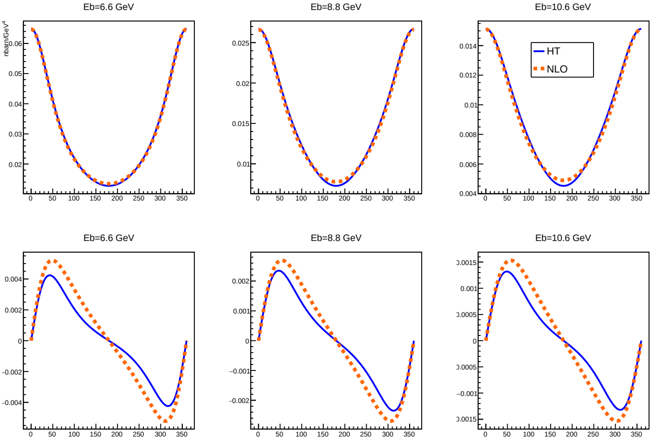
- Kinematical power corrections are sizeable at our moderate Q^2 (even at 4 GeV^2).
- Taking them into account, the leading-twist/leading-order fails to describe the data.
- Only conclusion is that we need higher-twist or Gluon GPDs at NLO.

Although it is an important conclusion... it is also disappointing that we have only a partial answer.
And people seem a bit skeptical about these kinematical power corrections.
How to convince everyone?
What are we looking at?
Finally it is less straightforward to know what we are measuring with photon electroproduction because of the Bethe-Heitler.

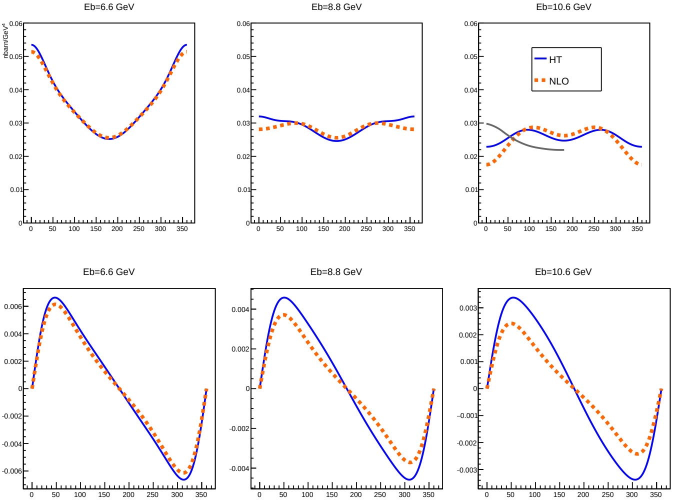
What can we expect from 12 GeV era? In Hall A, 2014

Data has been collected at 6.6 (Q^2=3.2), 8.8 (Q^2=3.6) and 10.6 GeV (Q^2=4.2) in Hall A, still at xB=0.36.

Assuming Q^2-independence (I would have tried to do something better but lack of time), we can expect this:



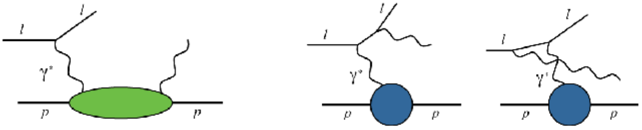
If we stay at Q^2=2, but use higher beam energy



- High Q^2 to "increase" the validity of Leading-twist/Leading-order assumptions.

Do a clean separation, assumption-free, with positrons!

Positrons beam is a solution to get a clean picture of the $DVCS^2$.



DVCS Bethe-Heitler

$$\frac{d^4\sigma(\lambda, \pm e)}{dQ^2 dx_B dt d\phi} = \frac{d^2\sigma_0}{dQ^2 dx_B} \frac{2\pi}{e^6} \times \left[\left| \mathcal{T}^{BH} \right|^2 + \left| \mathcal{T}^{DVCS} \right|^2 \mp \mathcal{I} \right] ,$$

with λ the helicity of the electron.

Think better about the next measurements

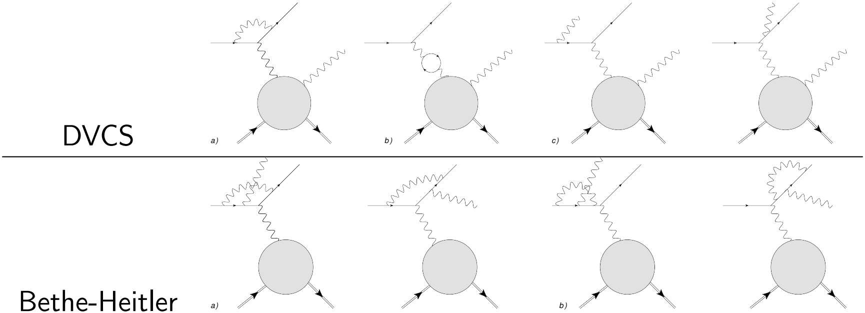
I have the feeling that people think we just need to measure accurately cross sections. But there are still many questions left to be answered and we need to keep an open-mind:

- We tried to test scaling to check the regime in JLab. Still need to be done.
- What is the weight of the different GPDs? 25% measurement of missing observables can be more constraining that 1%-accuracy on unpolarized cross sections.
  Don't we have a lot of answers if we do a simultaneous analysis of DVCS and DVMP?
- Bethe-Heitler is good as long as it is not most of the signal. Because we want to measure deviation from Bethe-Heitler.
- Run experiments to determine what we are measuring.
- What are the best observables? (Moments? or cross sections?)

Some warnings about the future

Technologically we are good. But upcoming data will require:

- the finest data analysis ever made at JLab. (Systematics at 1%?)
- intense theoretical effort for the radiative corrections,...!



The radiative corrections are different for $\mathcal{I}$, $|\mathcal{T}_{DVCS}|^2$ and $|\mathcal{T}_{BH}|^2$

Conclusion

- Kinematical power corrections are large. They should be also present in DVMP:
  Could it explain the sharp rise of σ_{TL} when Q^2 decreases?
  Take χ_0 and χ into account for Rosenbluth separation?
- If π^0 teaches us something: You can have surprises about the dominant contribution.
- We are sensitive to gluon or 3-parton correlations in DVCS. Might have additionnal information with CLAS12 data.
- But positron beam would be the cleanest way to access DVCS^2, which will immediately tell us what's going on.
- Not a single experiment/facility/channel will reconstruct the GPD puzzle. PARTONS!
- DSE gives already DAs for mesons... very good for DVMP analysis. It will also be interesting when they will deliver us a GPD for the nucleon. But I think both experiment and non-perturbative approached are required to perform the tomography of the nucleon.