Photon and π^0 electroproduction at Jefferson Laboratory - Hall A

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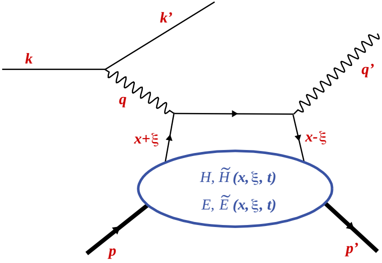
CEA Saclay - IRFU/SPhN

September 11^{th} 2015

DVCS and GPDs



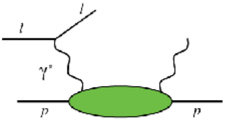
- $Q^2 = -q^2 = -(k-k')^2$.
- $x_B = \frac{Q^2}{2p \cdot q}$
- x longitudinal momentum fraction carried by the active quark.
- $\xi = \frac{x_B}{2-x_B}$ the longitudinal momentum transfer.
- $t = (p-p')^2$ squared momentum transfer to the nucleon.

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

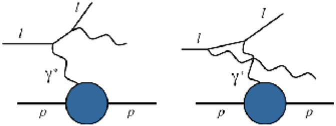
$$\mathcal{H}(\xi, t) = \int_{-1}^{1} H(x, \xi, t) \left(\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon} \right) dx \,.$$

Photon electroproduction and GPDs

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



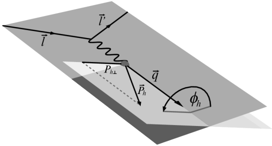
DVCS



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.



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

Goals and kinematics of the experiments

The CFFs are encapsulated in the ϕ-harmonics and offer a parameterization of the cross section:

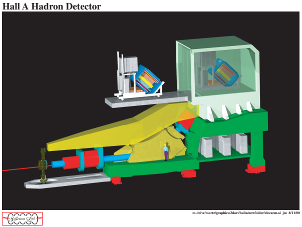
$$
\begin{aligned}
c_0^{DVCS} &\propto \quad \mathcal{C}^{DVCS}(\mathcal{F},\mathcal{F}^*) = 4(1-x_B)\mathcal{H}\mathcal{H}^* + \cdots \qquad (1)\\
c_1^{\mathcal{I}} &\propto \quad Re\ \mathcal{C}^{\mathcal{I}}(\mathcal{F}) = F_1\ Re\mathcal{H} + \xi(F_1+F_2)\ Re\widetilde{\mathcal{H}} - \frac{t}{4M^2}F_2\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

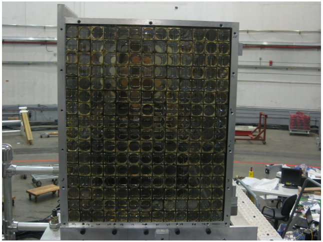
Mueller D., Belitsky A.V., Phys.Rev.D.82 (2010)

Initial goal: Study the Q^2-dependence of the CFFs in the valence region (x_B=0.36).

The experimental setup (pioneering experiment)

The experiment ran in 2004 at Jefferson Lab-Hall A (80% longitudinally polarized beam at 5.75 GeV).





- The High Resolution spectrometer detects and characterizes the scattered electron:
  It allows an accurate measurement of Q^2 and x_B.
- The electromagnetic calorimeter (PbF_2) detects the photon:
  It allows an accurate measurement of t and ϕ.

Missing mass and exclusivity

The exclusivity is ensured by cutting on the missing mass:

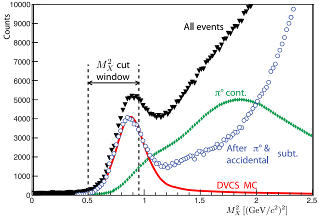
$$M^2_{ep\to e\gamma X} = (e + p - e' - \gamma)^2$$

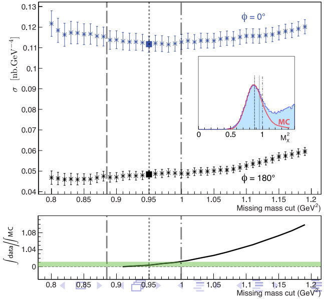
with three sources of contamination:

- Accidental (out-of-time) events.
- $\pi^0 \to \gamma\gamma$ events. Subtracted using the experimental data.
- SIDIS contamination removed by cutting on the missing mass.

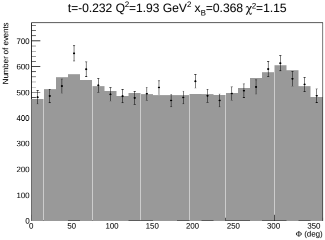
A lot of improvements in the analysis:

- More data points!
- Normalization
- Monte-Carlo simulation
- Contamination subtraction,...





An example of extraction



We have to parameterize :

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

For $d^4\sigma = \frac{1}{2}\left(\frac{d^4\sigma^{\rightarrow}}{dQ^2 dx_B dt d\phi} + \frac{d^4\sigma^{\leftarrow}}{dQ^2 dx_B dt d\phi}\right)$,
we assume $c_0^{\mathcal{I}} = 0$:

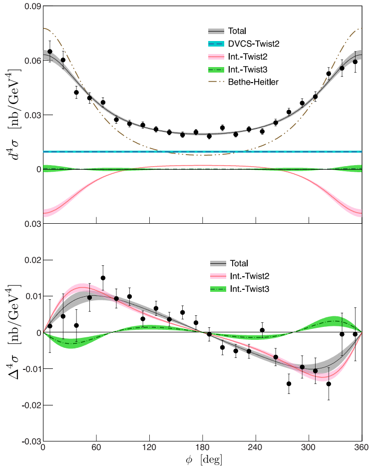
$$\left|\mathcal{T}_{DVCS}\right|^2 \simeq c_0^{DVCS}$$

$$\mathcal{I} \simeq c_1^{\mathcal{I}} \cos\phi + c_2^{\mathcal{I}} \cos 2\phi$$

For $\Delta^4\sigma = \frac{1}{2}\left(\frac{d^4\sigma^{\rightarrow}}{dQ^2 dx_B dt d\phi} - \frac{d^4\sigma^{\leftarrow}}{dQ^2 dx_B dt d\phi}\right)$:

$$\mathcal{I} \simeq s_1^{\mathcal{I}} \sin\phi + s_2^{\mathcal{I}} \sin 2\phi$$

An example of extraction



We have to parameterize :

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

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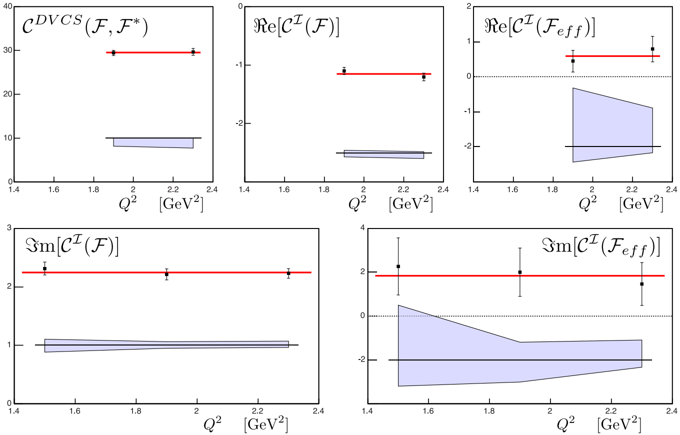
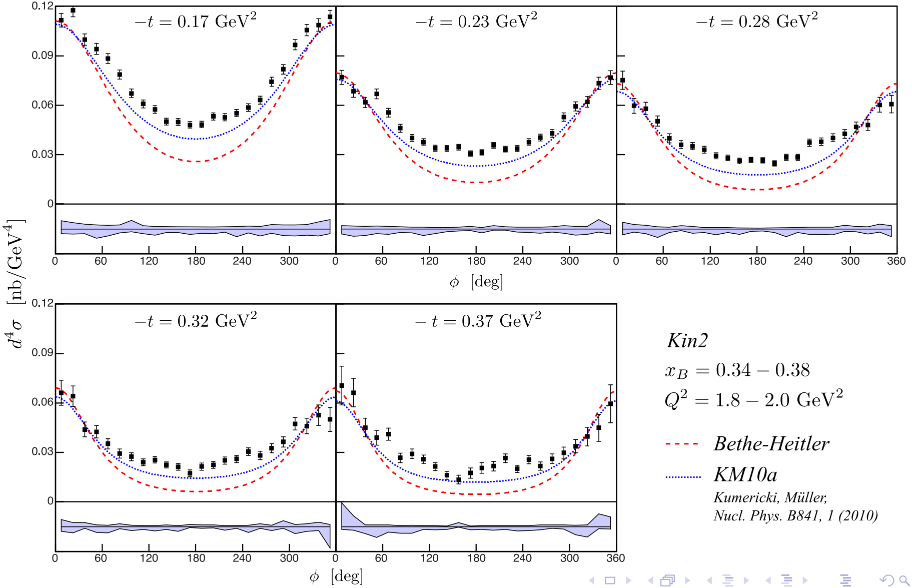
$$\mathcal{I} \simeq s_1^{\mathcal{I}}\sin\phi + s_2^{\mathcal{I}}\sin 2\phi$$

Q^2-dependence



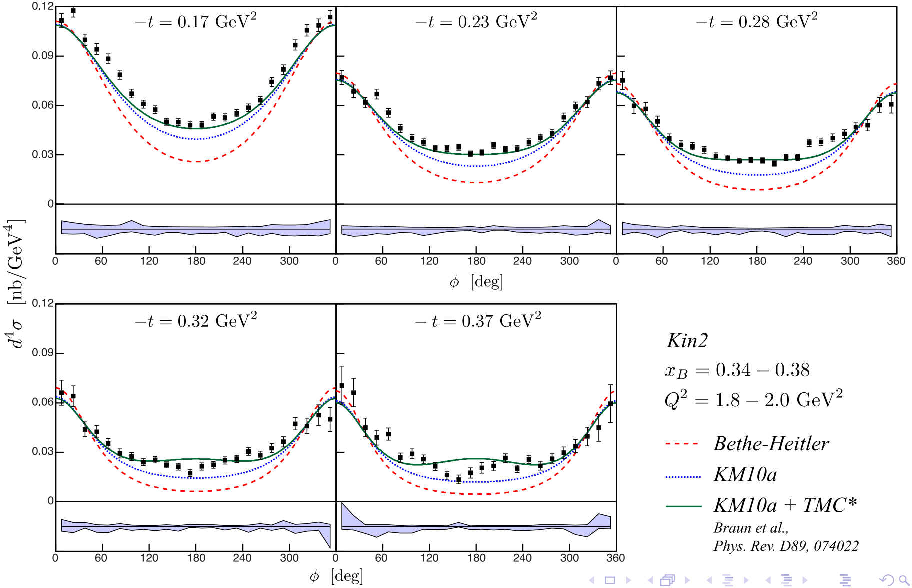
- Significant contribution of $|\mathcal{T}_{DVCS}|^2$.
- A large and Q^2-independent twist-2 contribution with slightly positive twist-3 contribution.

… up to twist-4?



$-t = 0.17$ GeV^2
$-t = 0.23$ GeV^2
$-t = 0.28$ GeV^2
$-t = 0.32$ GeV^2
$-t = 0.37$ GeV^2
$d^4\sigma$ [nb/GeV^4]
ϕ [deg]
Kin2
$x_B = 0.34 - 0.38$
$Q^2 = 1.8 - 2.0$ GeV^2
Bethe-Heitler
KM10a
Kumericki, Müller,
Nucl. Phys. B841, 1 (2010)

... up to twist-4?



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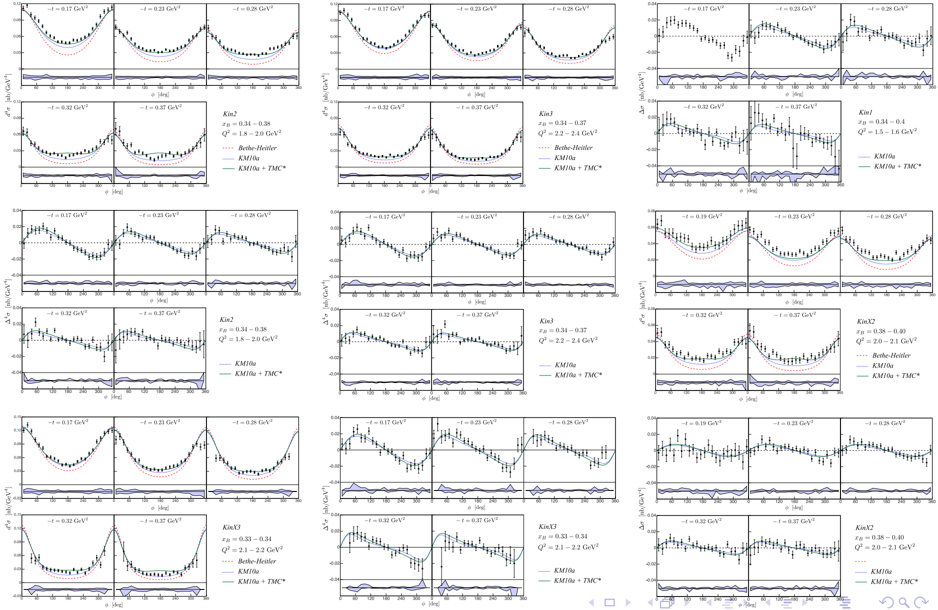
$-t = 0.37$ GeV^2
$d^4\sigma$ [nb/GeV^4]
ϕ [deg]
0.12
0.09
0.06
0.03
0
0 60 120 180 240 300 360
Kin2
$x_B = 0.34 - 0.38$
$Q^2 = 1.8 - 2.0$ GeV^2
Bethe-Heitler
KM10a
KM10a + TMC*
Braun et al.,
Phys. Rev. D89, 074022

A lot of new DVCS data



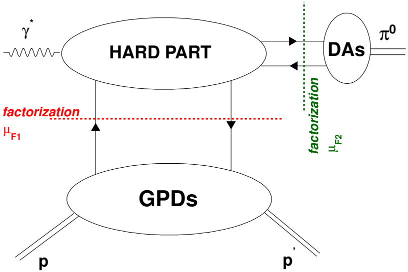
Conclusion on photon electroproduction

- There is a large contribution from $|\mathcal{T}_{DVCS}|^2$.
- The leading-twist contribution is the main contribution...
- but target-mass and finite-t corrections (up to twist-4) seem to explain the strong signal observed at 180° and which is not predicted by the leading twist models.
  M. Defurne *et al.* (Hall A collaboration), nucl-ex:1504.05453 (submitted to PRC) (2014)
- Coming soon... Rosenbluth separation of photon electroproduction cross section for early 2016.

Complicated systematic uncertainties that can be propagated only by the analysis team (exclusivity)!
It is time to define standard observables (Fourier coefficients, cross sections,...)

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.

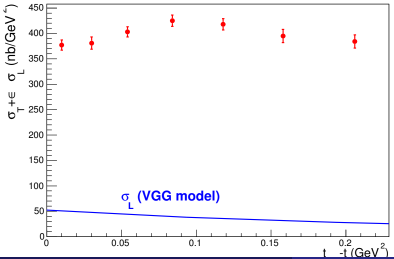
$$\mathcal{M} = GPDs(x, \xi, t, \mu_{F1}) \otimes HARD(x/\xi, z, \mu_{F1}, \mu_{F2}) \otimes DA(z, \mu_{F2})$$

Cross section and twist

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

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

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!



Hall A DVCS experimental setup suited also for π^0 studies.

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

ϵ=0.651

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

Cross section and twist

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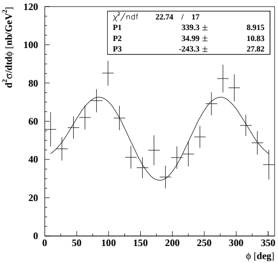


$Q^2 = 1.75$ GeV^2, $x_B = 0.22$, t'=0.12 GeV^2
ϵ=0.457

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 (assuming factorization). Ahmad, Goldstein, Liuti, PRD79, 054014(2009)
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.

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

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

Goloskokov S. and Kroll P.,Eur.Phys.Jour.A 47:112 (2011)

The first Rosenbluth separation of π^0 electroproduction

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

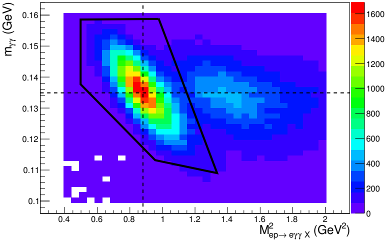
$$\frac{d^4\sigma}{dt d\phi dQ^2 dx_B} = \frac{1}{2\pi}\Gamma_{\gamma^*}(Q^2, x_B, E_e)\Big[\frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi)\Big],$$

New experiment in 2010 with same experimental setup than in 2004.
(Jefferson Lab, Hall A spectrometer and calorimeter)

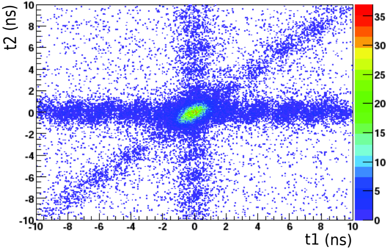
Setting	E (GeV)	Q^2 (GeV^2)	x_B	ϵ
2010-Kin1	(3.355 ; 5.55)	1.5	0.36	(0.52 ; 0.84)
2010-Kin2	(4.455 ; 5.55)	1.75	0.36	(0.65 ; 0.79)
2010-Kin3	(4.455 ; 5.55)	2	0.36	(0.53 ; 0.72)

Selection of exclusive π^0 events

Since $M^2_{ep\to e\gamma\gamma X}$ and $m_{\gamma\gamma}$ are correlated, we apply a 2D-cut to ensure exclusivity and particle identification.



$$N_{\mathfrak{e}} = N_{ep\to ep\pi^0} + N_{acc} + N_{SIDIS} \ ,$$

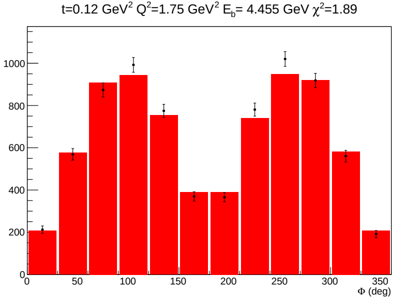


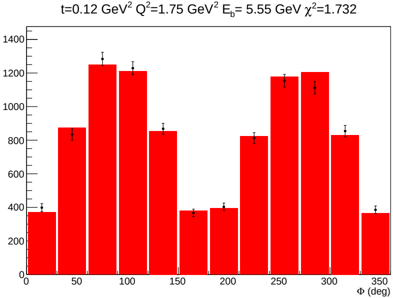
Several accidental cases:

- $e\pi^0$ given by the diagonal.
- $e\gamma\gamma$ given by the horizontal or vertical line.
- $e\gamma\gamma$ everywhere.

Finally...

We fit $\frac{d\sigma_T}{dt}$, $\frac{d\sigma_L}{dt}$, $\frac{d\sigma_{TL}}{dt}$, $\frac{d\sigma_{TT}}{dt}$ in order to reproduce the number of counts (MC in red and experimental in black) at the two beam energies:

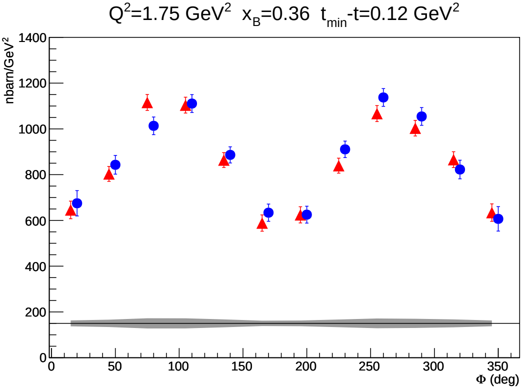




Finally...

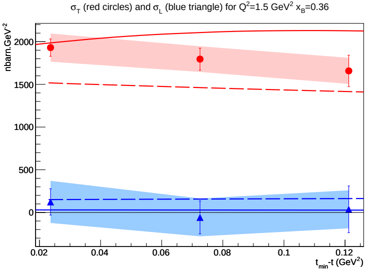
$$\frac{d\sigma}{dt} = \frac{d\sigma_T}{dt} + \epsilon\frac{d\sigma_L}{dt} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{TL}}{dt}cos(\phi) + \epsilon\frac{d\sigma_{TT}}{dt}cos(2\phi),$$

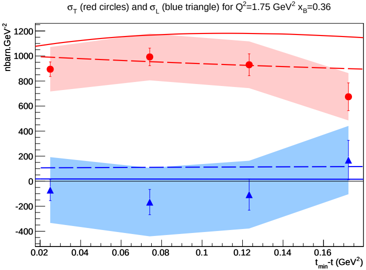
$\epsilon =$ 0.65

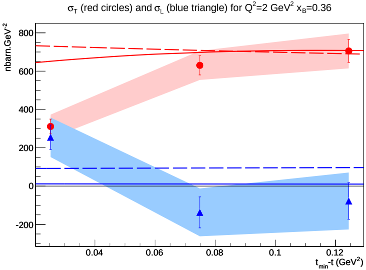


$\epsilon =$ 0.79

Results (PRELIMINARY)







Kroll-Goloskokov (solid line)

Goloskokov S. and Kroll P.,Eur.Phys.Jour.A 47:112 (2011)

Goldstein-Liuti (dashed line)

Goldstein *et al.*, PRD91, 114013 (2015)

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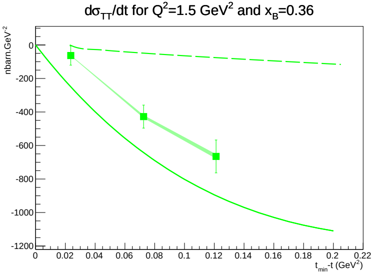

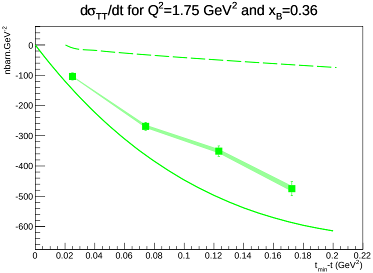

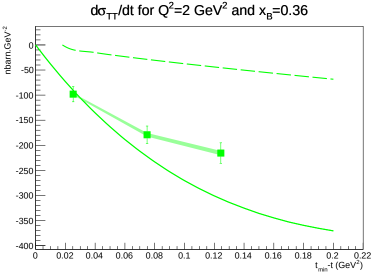

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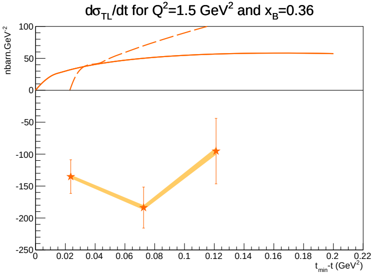

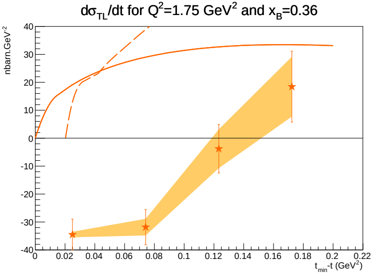

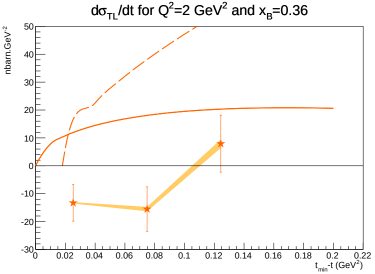

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Goldstein *et al.*, PRD91, 114013 (2015)

Conclusion on π^0 electroproduction

- The longitudinal response is found compatible with 0 except at small t and Q^2=2 GeV^2.
- Unlike DVCS, the leading-twist contribution is not the main contribution.
- The fair agreement between the transversity-GPD models and the data seems to indicate that there might be a coupling between the transversity GPDs and the twist-3 DAs of the pion.
- The π^0's are convenient to study $\widetilde{H}$, $\widetilde{E}$ (at Q^2 large enough) and also allow to access the elusive transversity GPDs $\widetilde{H}_T$ et E_T.

Global conclusion

- Both processes can be interpreted at the partonic scale.
- Nevertheless, at our moderate Q^2-values, we cannot restrain this interpretation at the leading-twist contribution.
- But what about the neglected twist-3 and -4 contributions?
- What about the gluonic contributions appearing at NLO in photon electroproduction?

There are still a lot that we need to investigate.
Next years will be exciting for the GPDs with the upgrade of JLab accelerator and the future EIC!