

Timelike Compton Scattering off the nucleon and experimental perspectives for JLab

Annual meeting of the GDR PH-QCD
Dec. 15th - 17th 2014, école polytechnique

Marie Boér

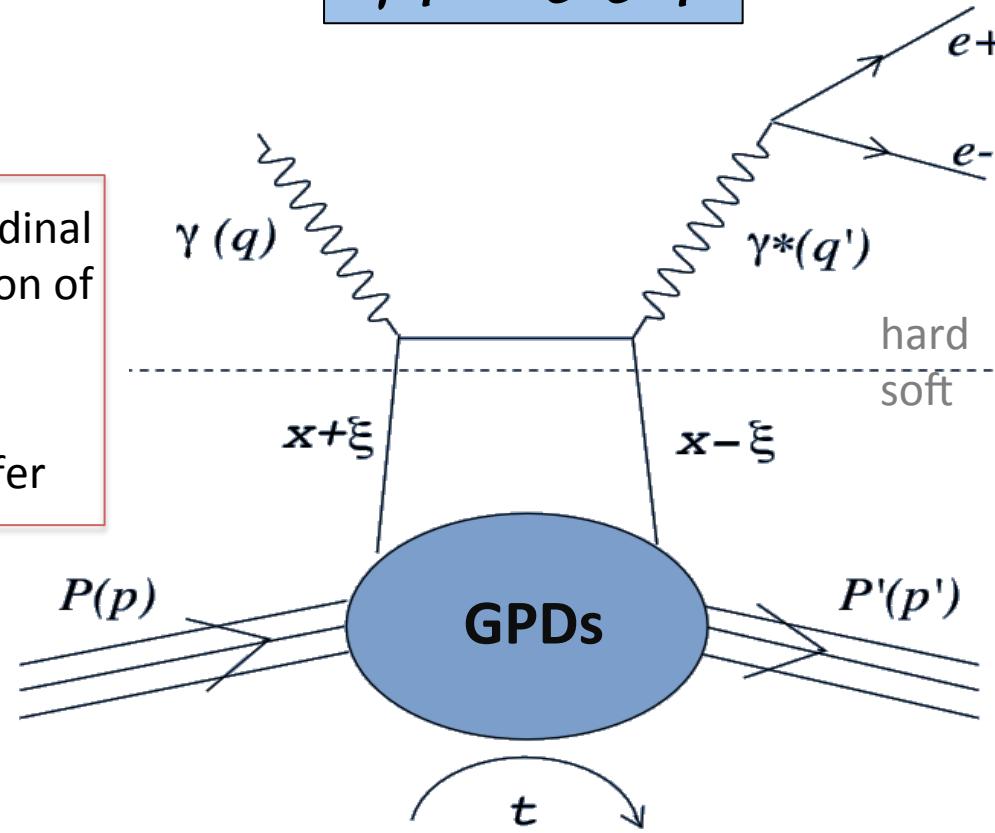
Work in collaboration with M. Guidal and M. Vanderhaeghen

Timelike Compton Scattering

$$\gamma \mathcal{P} \rightarrow e^+ e^- \mathcal{P}$$

x : average longitudinal momentum fraction of the struck quark

ξ : longitudinal momentum transfer



$Q'^2 \gg 1 \text{ GeV}^2$
hard scale

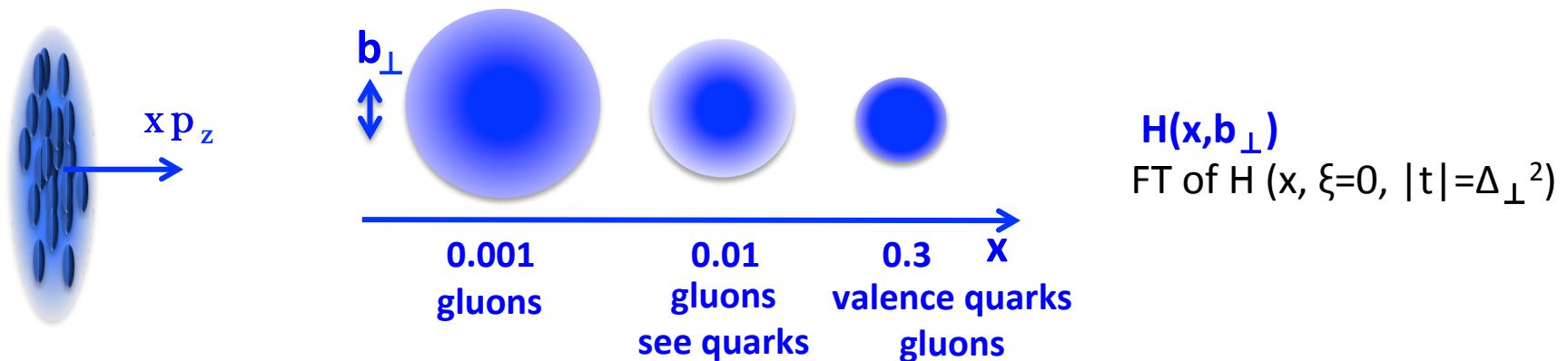
$t \ll Q'^2$
momentum transfer

Exclusive process: measurement of t and ξ

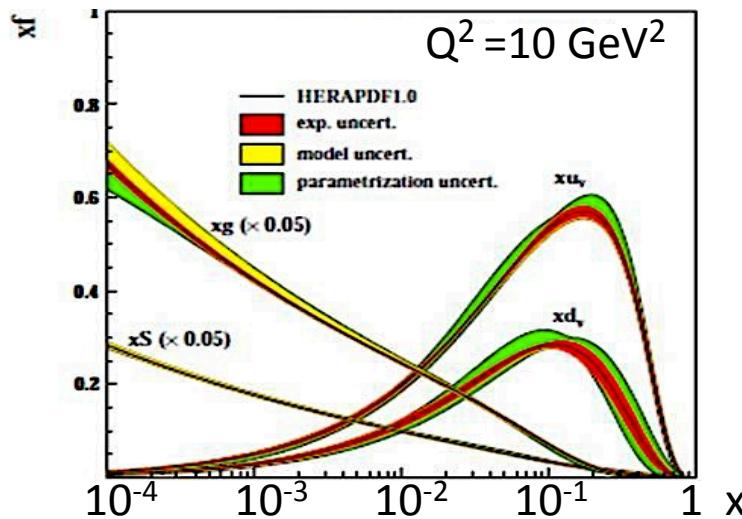
Soft part: Generalized Partons Distributions $\rightarrow \text{GPD}(x, \xi, t; Q'^2)$

Interpretation of GPDs

Correlation between longitudinal momentum fraction x and transverse charge densities



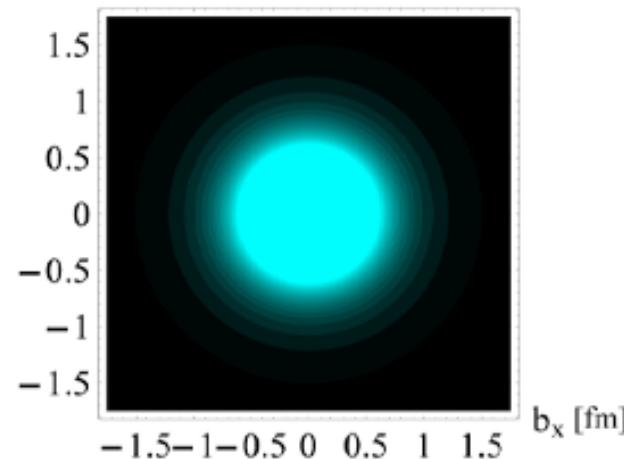
Parton Distribution from HERA fits
 $q(x) = H (x, \xi=0, t=0)$



$$t = 0$$

$$\int dx$$

Transverse charge density from
Form Factors $\Rightarrow \text{FT}[F_1(t)]$



Context of TCS studies

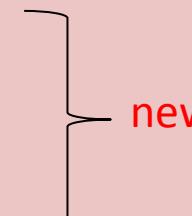
Theory

- σ unpolarized and circularly beam polarized (2002)¹, linearly polarized (2014)²
- DVCS and TCS at NLO^{3,4} (+ ... for DVCS)

Experiment (JLab)

- Faisability studies at CLAS 6 GeV⁵
- ↳ Proposal accepted for CLAS12⁶: σ_{unpol}
Letter of intend: Hall A SOLID⁷

This work

- Calculation of cross sections using VGG model
 - unpolarized → removing some t/Q^2 approximations
 - polarized γ beam
 - polarized proton or neutron target
 - Observables studies and GPDs dependencies
 - Some higher twist corrections
- 
- new

¹Berger, Diehl, Pire, E.P.J. C23 (2002) 675

²Goritschnig, Pire, Wagner, arXiv:1404.0713 (2014)

³Pire, Szymanowski, Wagner, PRD 83 (2011) 034009

⁴Moutarde, Pire, Sabatié, Szymanowski, Wagner, PRD 87 (2013) 5, 054029

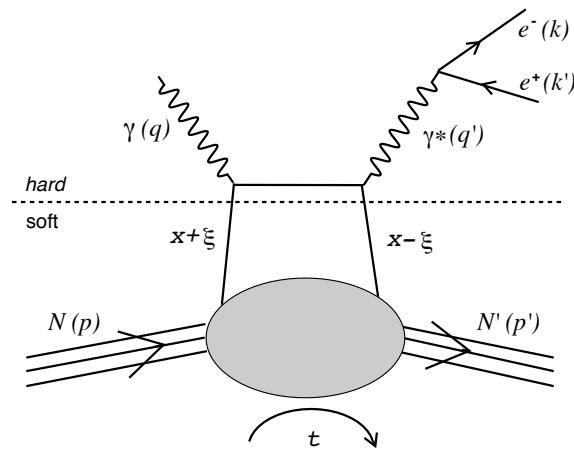
⁵Paremuzyan, PhD

⁶JLab PAC39

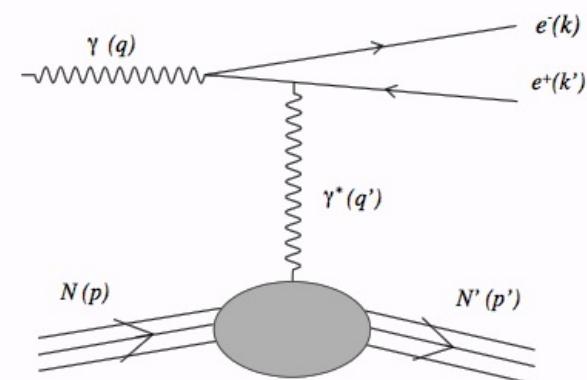
⁷JLab PAC40

TCS and exclusive lepton pair photoproduction

$$\gamma N \rightarrow e^+ e^- N =$$



+



**Timelike Compton Scattering (TCS)
sensitive to the nucleon GPDs**

**Bethe-Heitler (BH)
sensitive to the nucleon Form Factors**

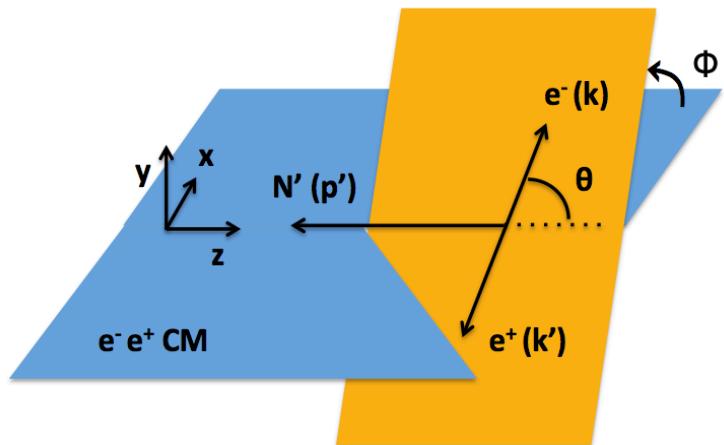
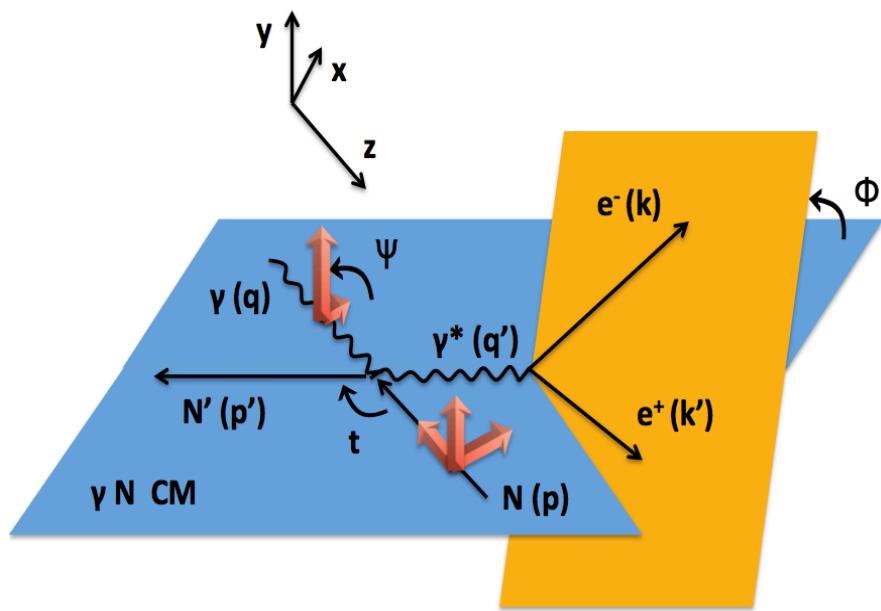
$$\frac{d^4\sigma}{dQ'^2 dt d\Omega} (\gamma p \rightarrow p' e^+ e^-) = \frac{1}{(2\pi)^4} \frac{1}{64} \frac{1}{(2ME_\gamma)^2} | T^{BH} + T^{TCS} |^2$$

Angles and notations

$\gamma N \rightarrow e^+e^- N$

$$\frac{d\sigma}{dQ'^2 dt d\phi d(\cos\theta)}$$

Ψ : (reaction plane, γ spin)
 Φ : (hadronic plane, e^+e^- pair)
 Θ : (γ^* , e^-)



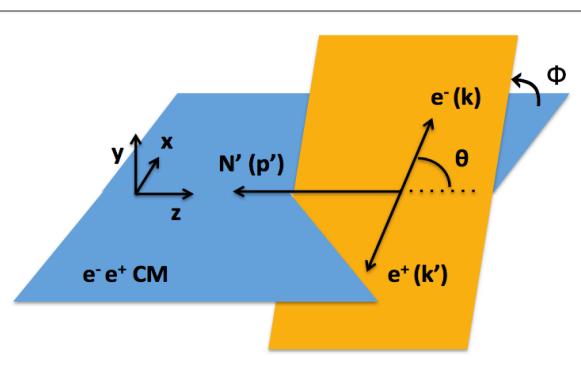
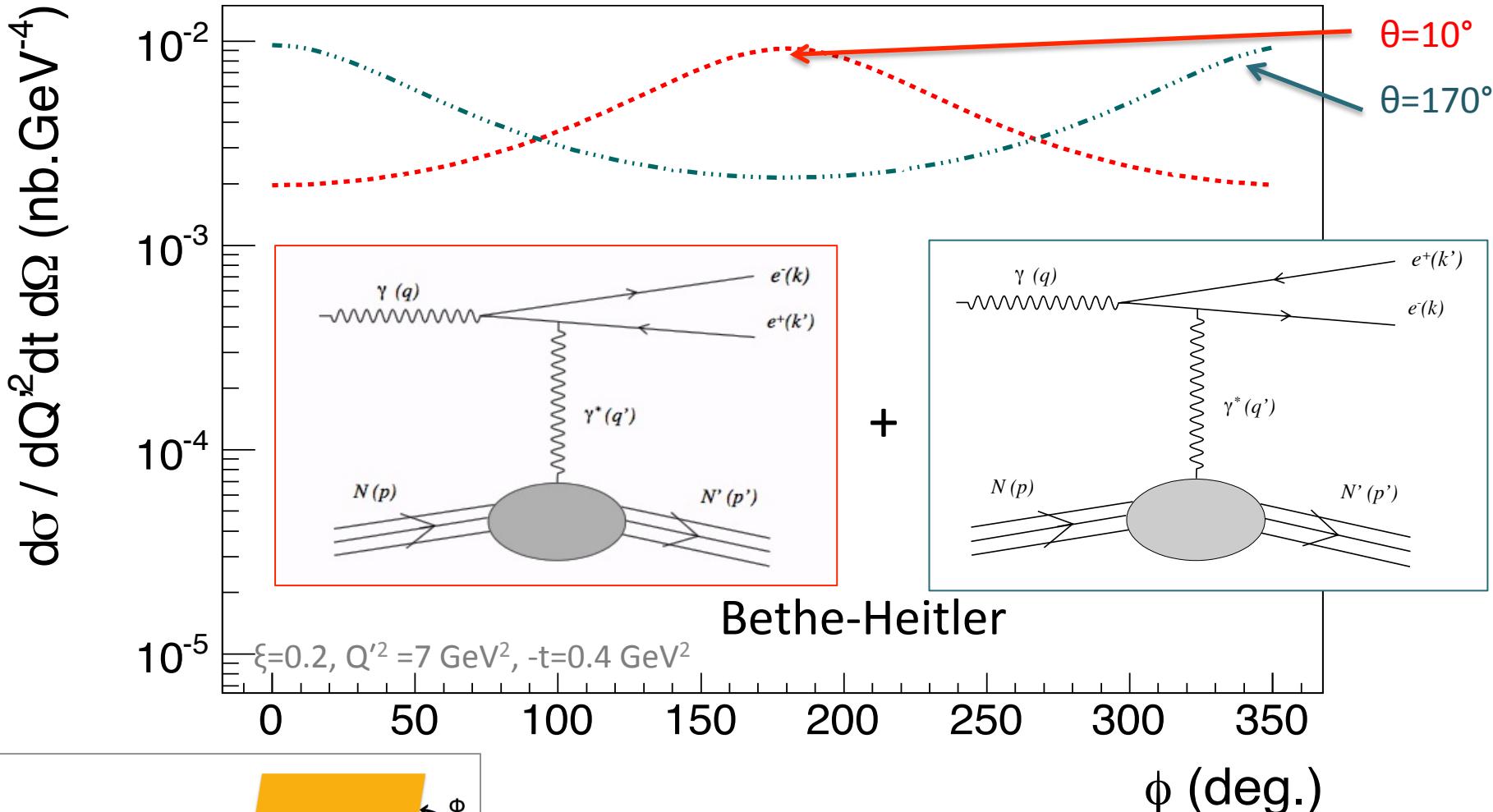
Notations

A_{ij} : asymmetry

1^{er} index: photon polarisation, \odot = circular, \mathbf{L} = linear, \mathbf{U} = unpolarized

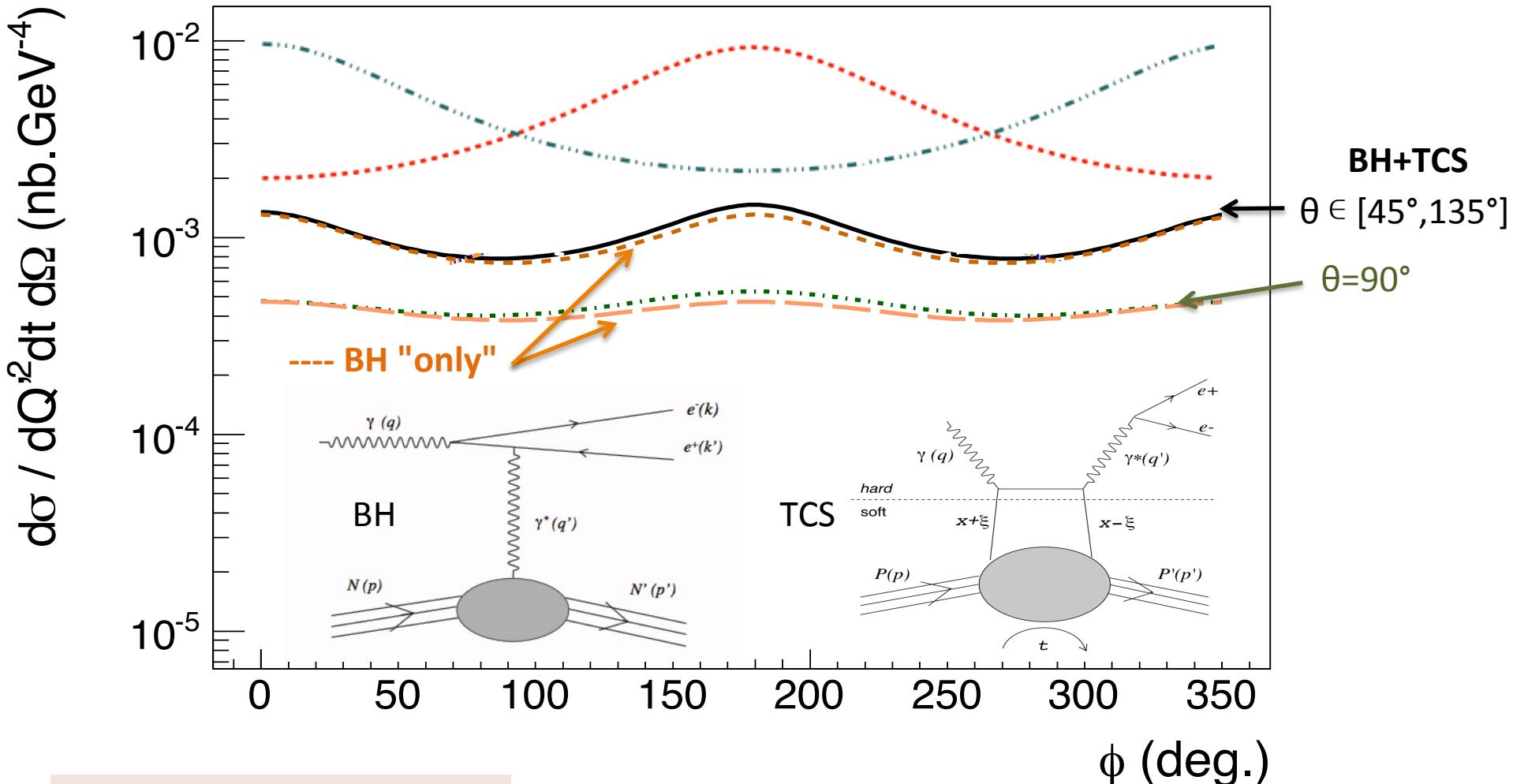
2^d index: nucleon polarisation, \mathbf{x} (transverse in plane), \mathbf{y} (transverse), \mathbf{z} (longitudinal)

Bethe-Heitler angular dependancies



e^- in γ direction ($\theta \rightarrow 0^\circ$) \Rightarrow Singularity at $\phi = 180^\circ$
 e^+ in γ direction ($\theta \rightarrow 180^\circ$) \Rightarrow Singularity at $\phi = 0^\circ$

Bethe-Heitler + TCS



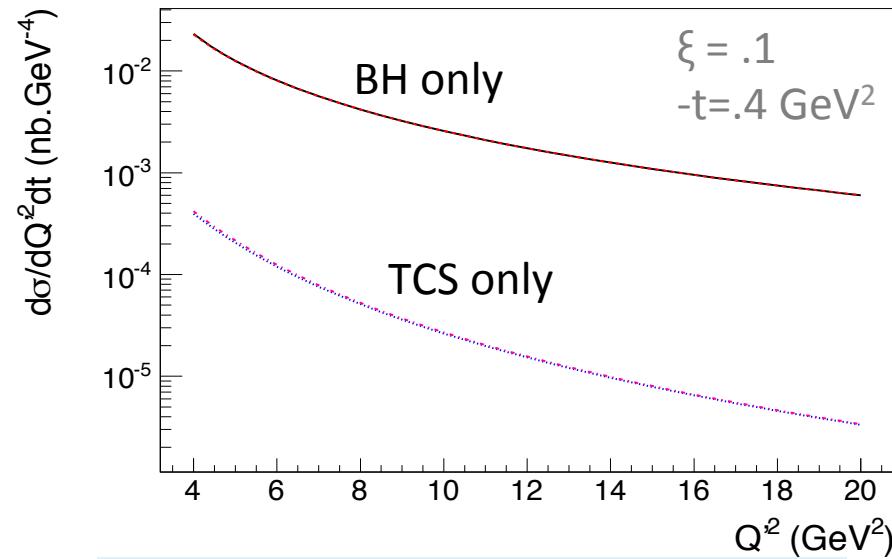
Bethe-Heitler dominant

$\theta = 90^\circ$: far from singularities, more important TCS/BH rate, sensitivity to interference

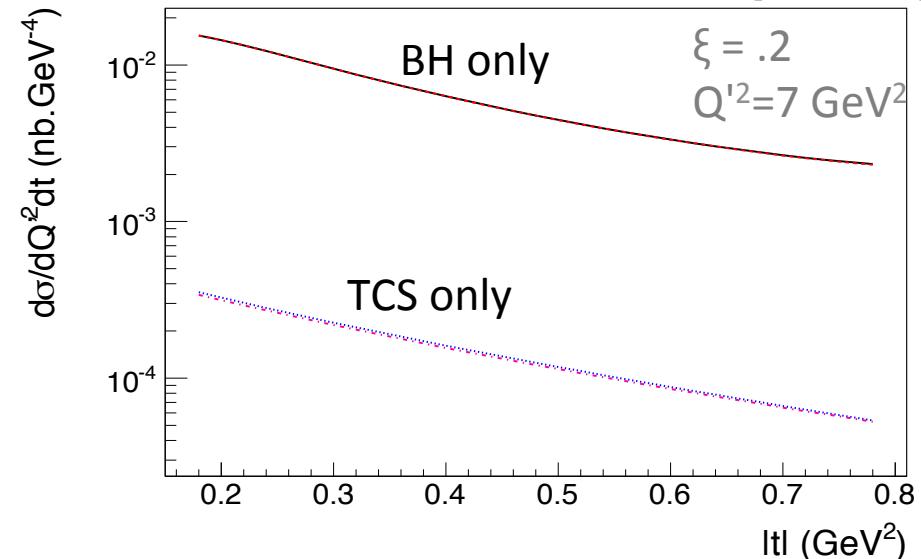
$\theta \in [45^\circ, 135^\circ] \Rightarrow$ integrated for statistics

Kinematical dependencies and comparisons

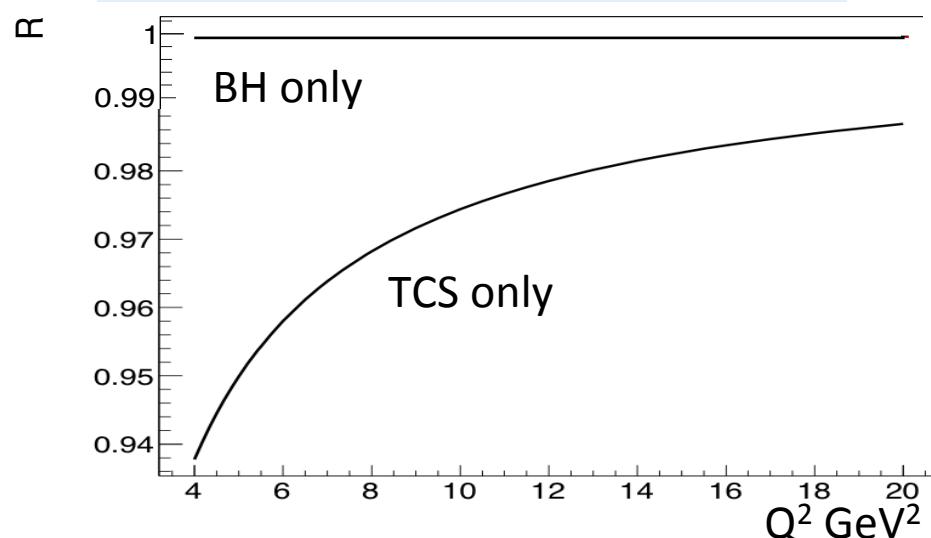
cross sections vs Q^2 and vs t



integrated over decay angles



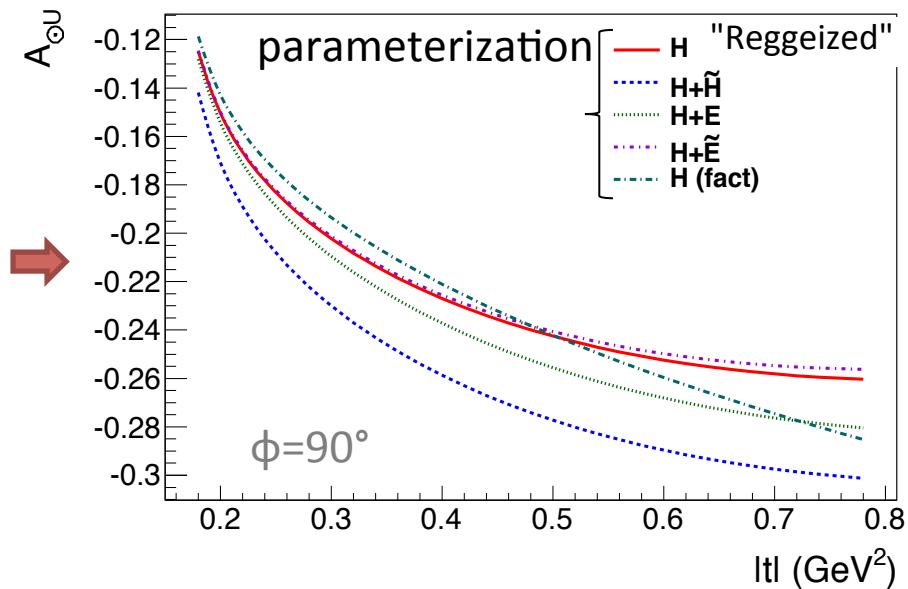
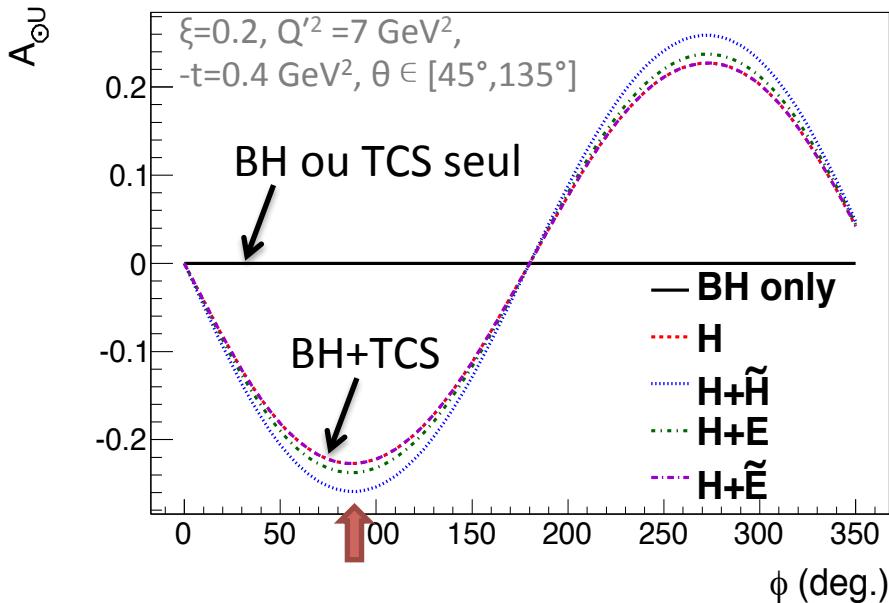
R = Berger, Diehl, Pire¹ / this work



- $\text{BH} \approx 100 \times \text{TCS}$
- order of pbarn
- Comparison Berger et al.
 - BH: \approx equal
 - TCS: few % at low Q^2 \rightarrow waived some t/Q^2 approximations

¹Berger, Diehl, Pire, E.P.J. C23 (2002) 675

Asymmetries: circularly polarized beam

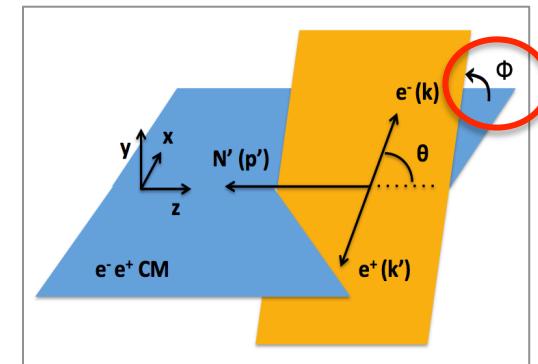


$A_{OU} \propto$ imaginary part of amplitudes $\Rightarrow A_{OU} = 0$ for Bethe-Heitler

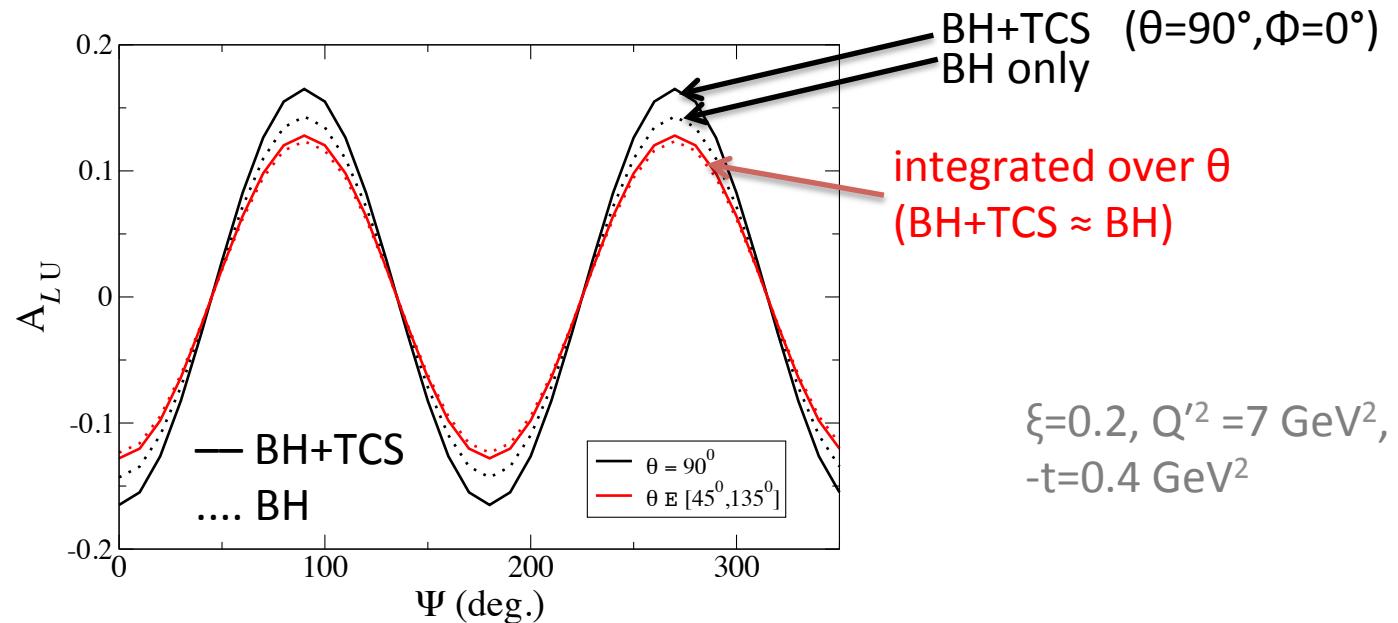
Asymmetry $\approx 20\%$

Mostly sensitive to H and \tilde{H}

$\approx 20\%$ asymmetry coming from interference
 BH x TCS and sensitive to GPDs

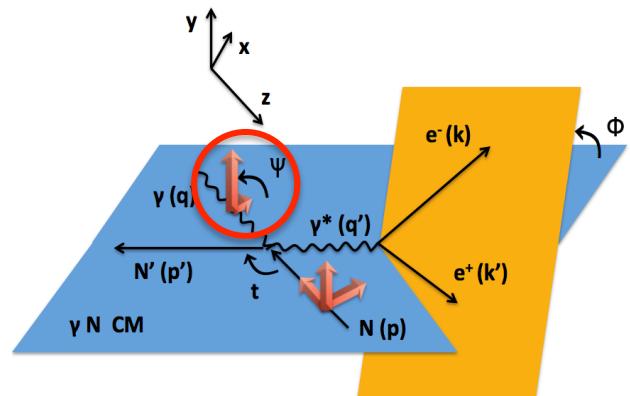


Asymmetry: linearly polarized beam



- Real part of amplitudes \Rightarrow BH only $\neq 0$
- Small deviation due to TCS, small sensitivity to the GPDs
- Bins in ϕ and θ required

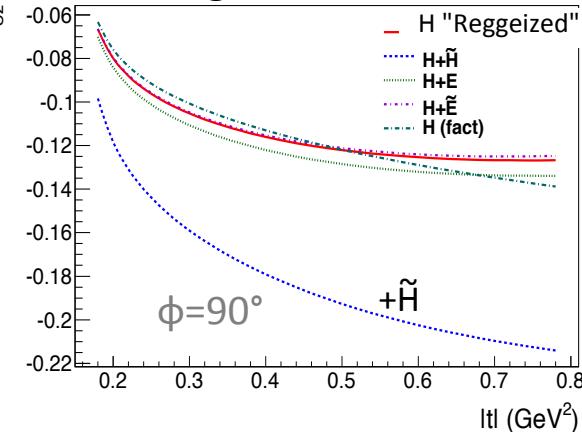
Unfavorable observable
for GPDs studies



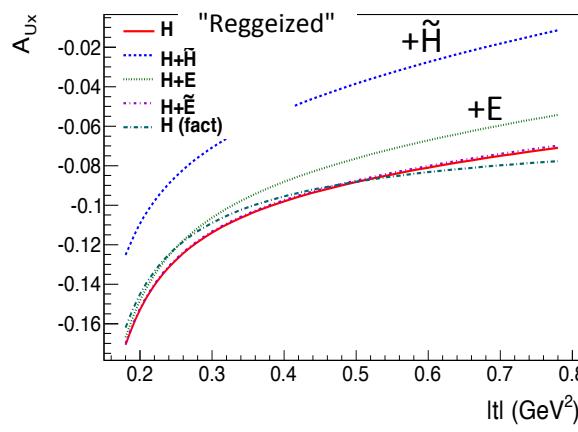
Asymmetries: polarized target

Single target polarization vs $|t|$

“longitudinal z”



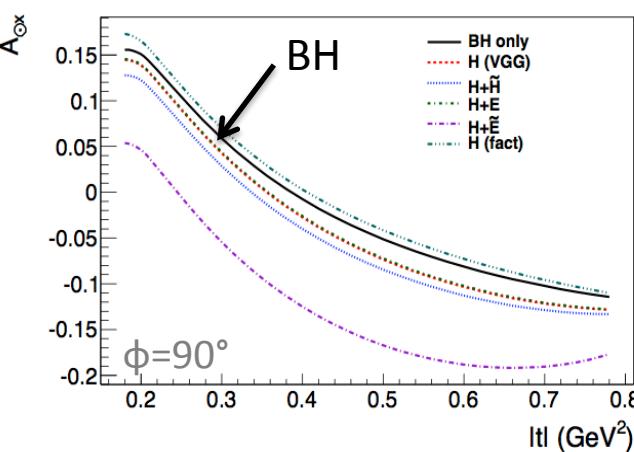
“transverse x”



- Im part of amplitudes
⇒ $A_{Ui} [BH] = 0$
- Sensitive to H, \tilde{H}, E

Double beam (circ.) and target polarization vs $|t|$

“circ.+ transverse x”



- Very sensitive to the GPDs parameterization
- But
- $A[BH] \neq 0$, few % deviation from TCS signal
- Bins in ϕ and θ preferable
- Experimental difficulties (stat...)

$$\xi=0.2, Q'^2=7 \text{ GeV}^2, -t=0.4 \text{ GeV}^2, \theta \in [45^\circ, 135^\circ]$$

Some mass terms restoration

"light cone coordinates"

$$\tilde{\xi} = \xi \cdot \frac{1 + \tilde{\xi}'^2 \frac{\bar{M}^2}{\bar{q}^2}}{1 - \tilde{\xi}'^2 \frac{\bar{M}^2}{\bar{q}^2}}$$

$$\tilde{\xi}' = \xi' \cdot \frac{2}{1 + \sqrt{1 - 4\xi'^2 \frac{\bar{M}^2}{\bar{q}^2}}}$$

kinematical variables
experimentaly accessible

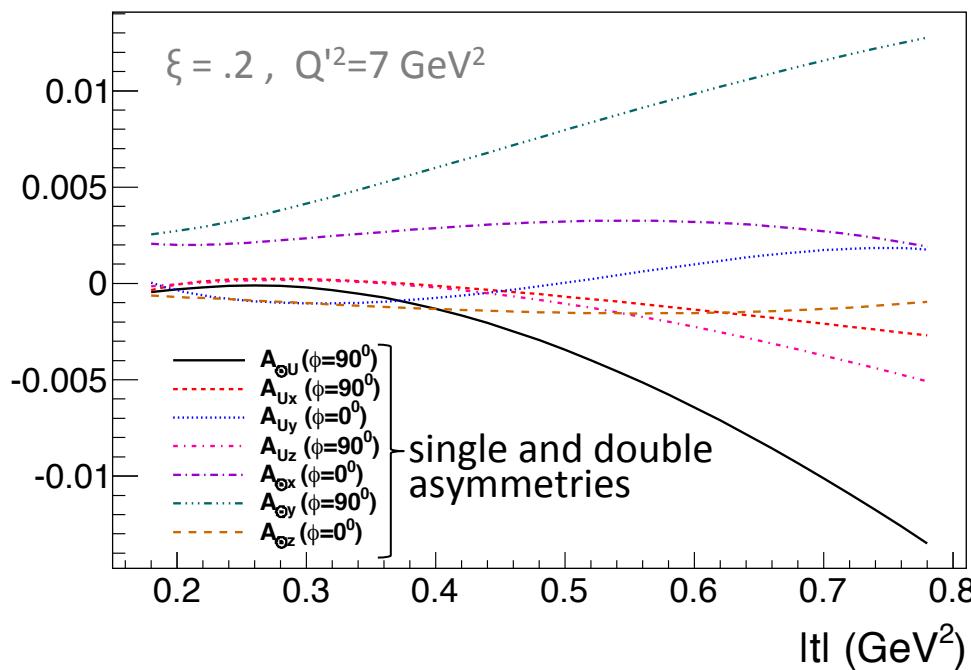
asymptotic limit (twist 2)
 Δ^2/Q^2 and $M^2/Q^2 \ll 1$

$$\xi' = -\frac{\bar{q}^2}{2P.\bar{q}} = \frac{-Q'^2 + \Delta^2/2}{2(s - m_N^2) + \Delta^2 - Q'^2}$$

$$\xi = -\frac{\Delta \cdot \bar{q}}{2P.\bar{q}} = \frac{Q'^2}{2(s - m_N^2) + \Delta^2 - Q'^2}$$

$$\tilde{\xi} = \xi = -\tilde{\xi}' = -\xi' = \frac{Q'^2}{2s - Q'^2}$$

Asymmetries: corrected – asymptotic



Mass correction: with $\xi' \neq \tilde{\xi}$

Corrections: <0.01 vs 0.10 to 0.30

Gauge invariance restoration

Gauge invariance: $q_\mu H^{\mu\nu} = q_\nu H^{\mu\nu} \equiv 0$

but $\sim q_\mu H^{\mu\nu}_{LO} = \frac{1}{2} (\Delta_\perp)_\kappa H^{\kappa\nu}_{LO}$ and $q'_\nu H^{\mu\nu}_{LO} = -\frac{1}{2} (\Delta_\perp)_\lambda H^{\kappa\lambda}_{LO}$

Twist 2 amplitudes are
not gauge invariant

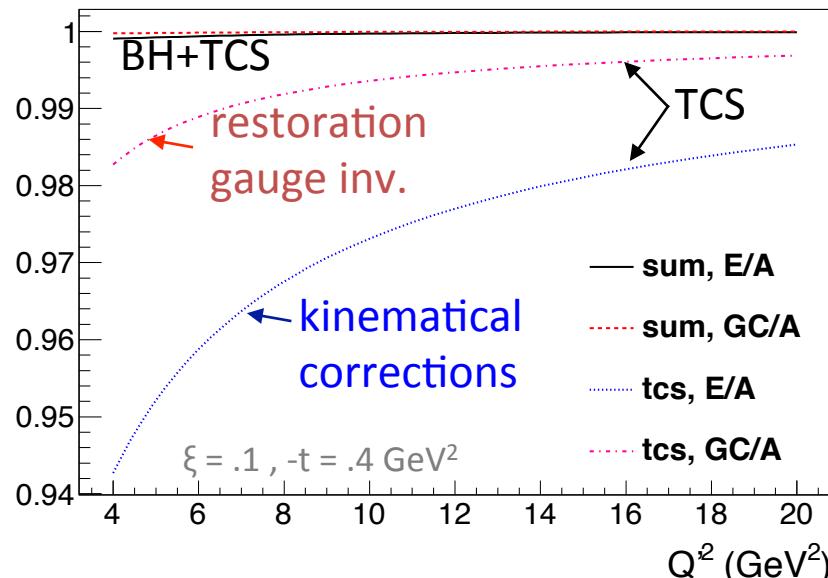
We restore gauge invariance with the correction¹:

$$H^{\mu\nu} = H_{LO}^{\mu\nu} - \frac{P^\mu}{2P \cdot \bar{q}} \cdot (\Delta_\perp)_\kappa \cdot H_{LO}^{\kappa\nu} + \frac{P^\nu}{2P \cdot \bar{q}} \cdot (\Delta_\perp)_\lambda \cdot H_{LO}^{\mu\lambda} - \frac{P^\mu P^\nu}{4(P \cdot \bar{q})^2} \cdot (\Delta_\perp)_\kappa \cdot (\Delta_\perp)_\lambda \cdot H_{LO}^{\kappa\lambda}$$

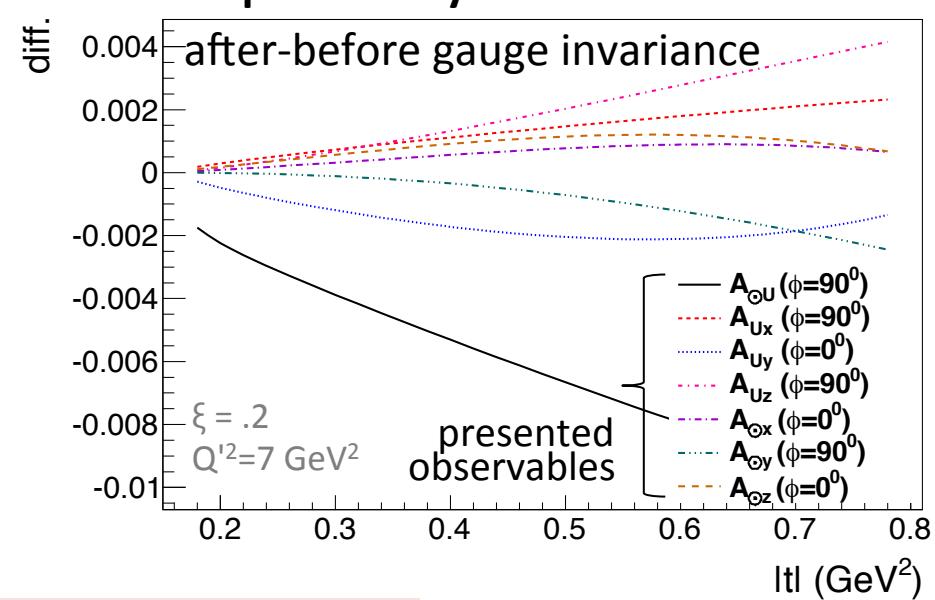
additional terms

twist 2
vector part

cross section after/before correction



Impact on asymmetries

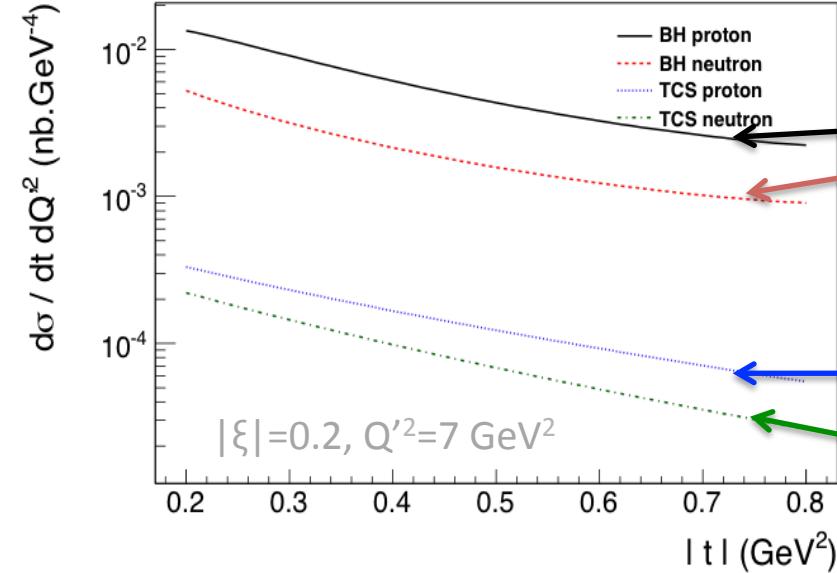


¹Vanderhaeghen, Guichon, Guidal,
PRD 60 (1999) 094017

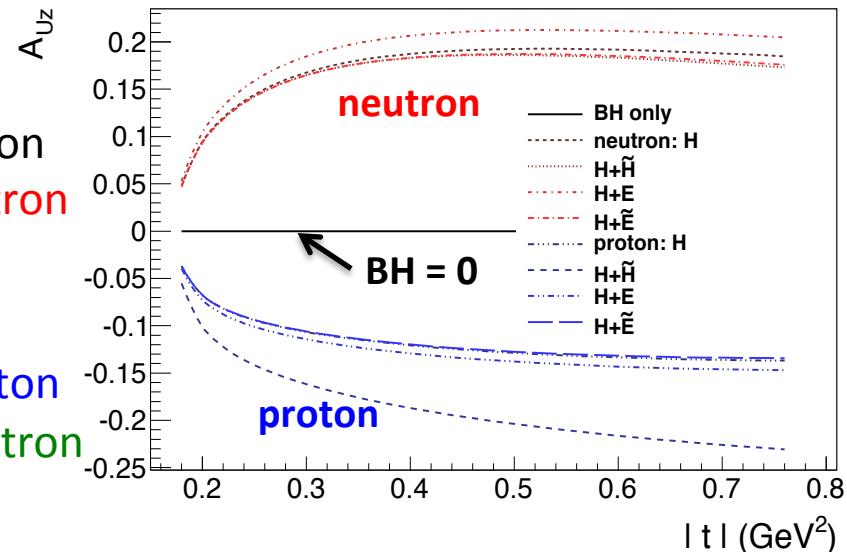
corrections \ll values of observables

TCS off the neutron

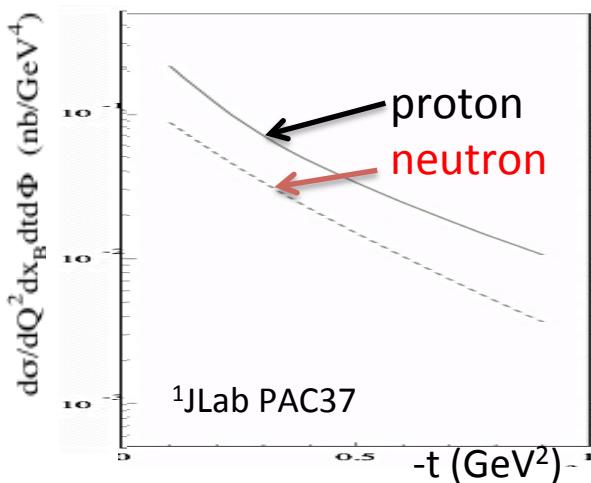
unpolarized cross sections



Longitudinally polarized target



Comparison: DVCS+BH¹

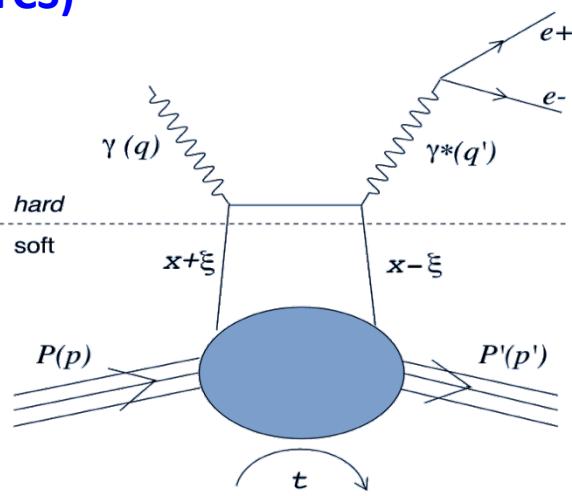


- flavor separation
- GPD E
- same suppression compared to DVCS off neutron
- Asymmetries \approx same Φ and t dependancies and size
- ⇒ TCS off neutron is measurable but is more difficult experimentally

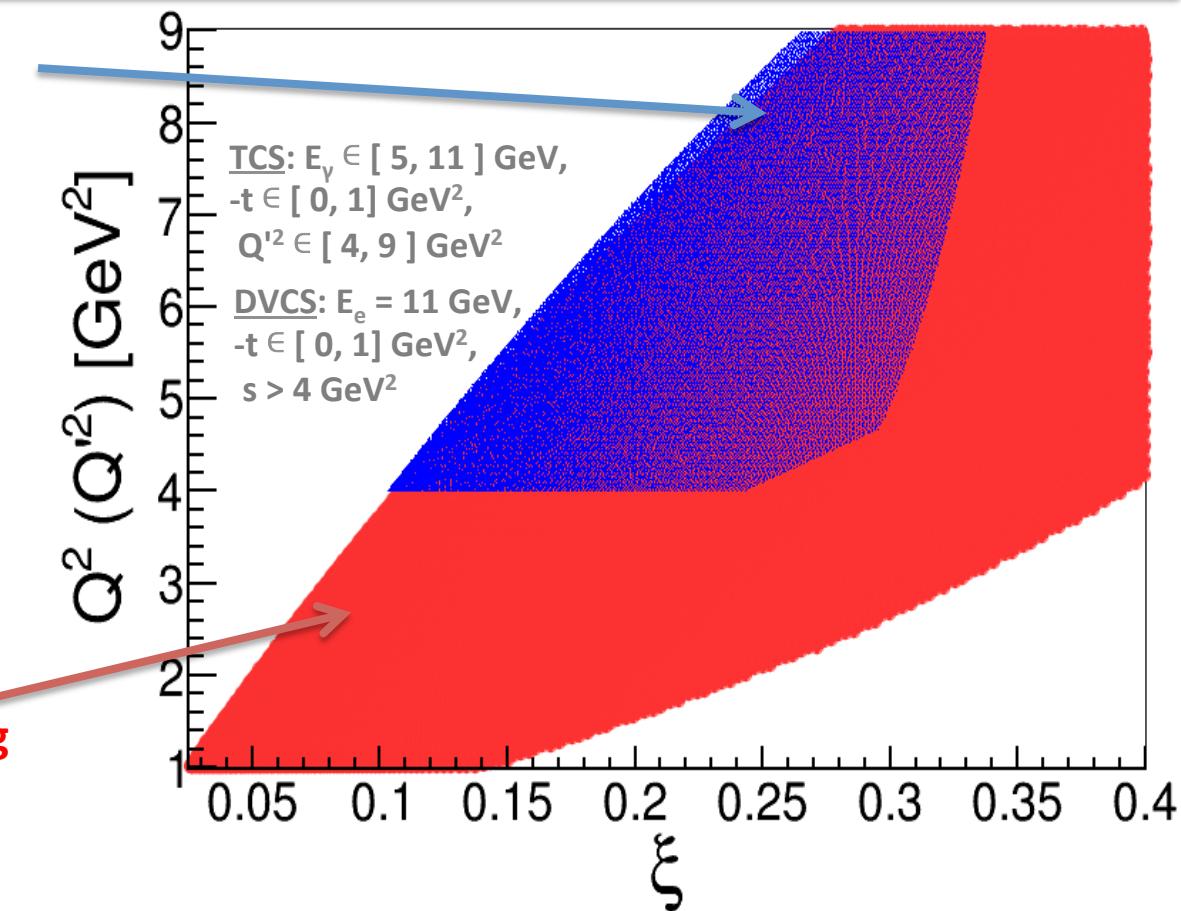
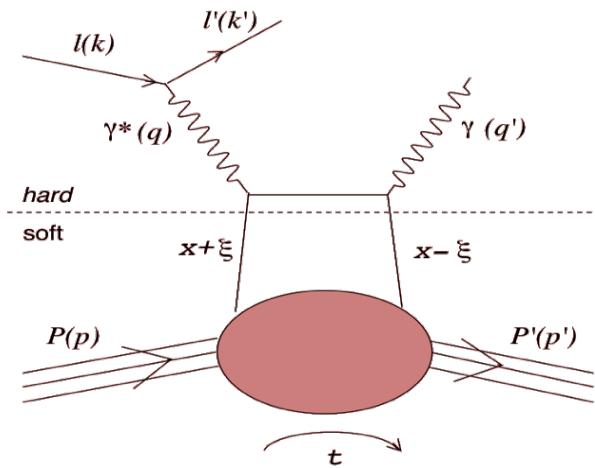
**From theoretical predictions
to future measurements...**

Phase Space for TCS and DVCS at JLab 12 GeV

Timelike Compton Scattering (TCS)



Deeply Virtual Compton Scattering (DVCS)



- Universality of GPDs
- Complementary observables
- Higher twist and higher order effects

Compton Form Factors with TCS fits

Could we extract CFFs from TCS fits ?

- Pseudo-data based on our TCS calculation
- DVCS¹ method is expanded for TCS and TCS+DVCS
- Local fits: MINUIT + MINOS
 - several sets of observables, (ξ, t) points fitted independently
 - 7 free parameters: CFFs ($\Im m$ and $\Re e [\mathcal{H}, \tilde{\mathcal{H}}, \mathcal{E}], \Re e[\tilde{\mathcal{E}}]$) , the variation of parameters is limited

¹M. Guidal, EPJA 37 (2008) 319

Compton Form Factors fits with TCS

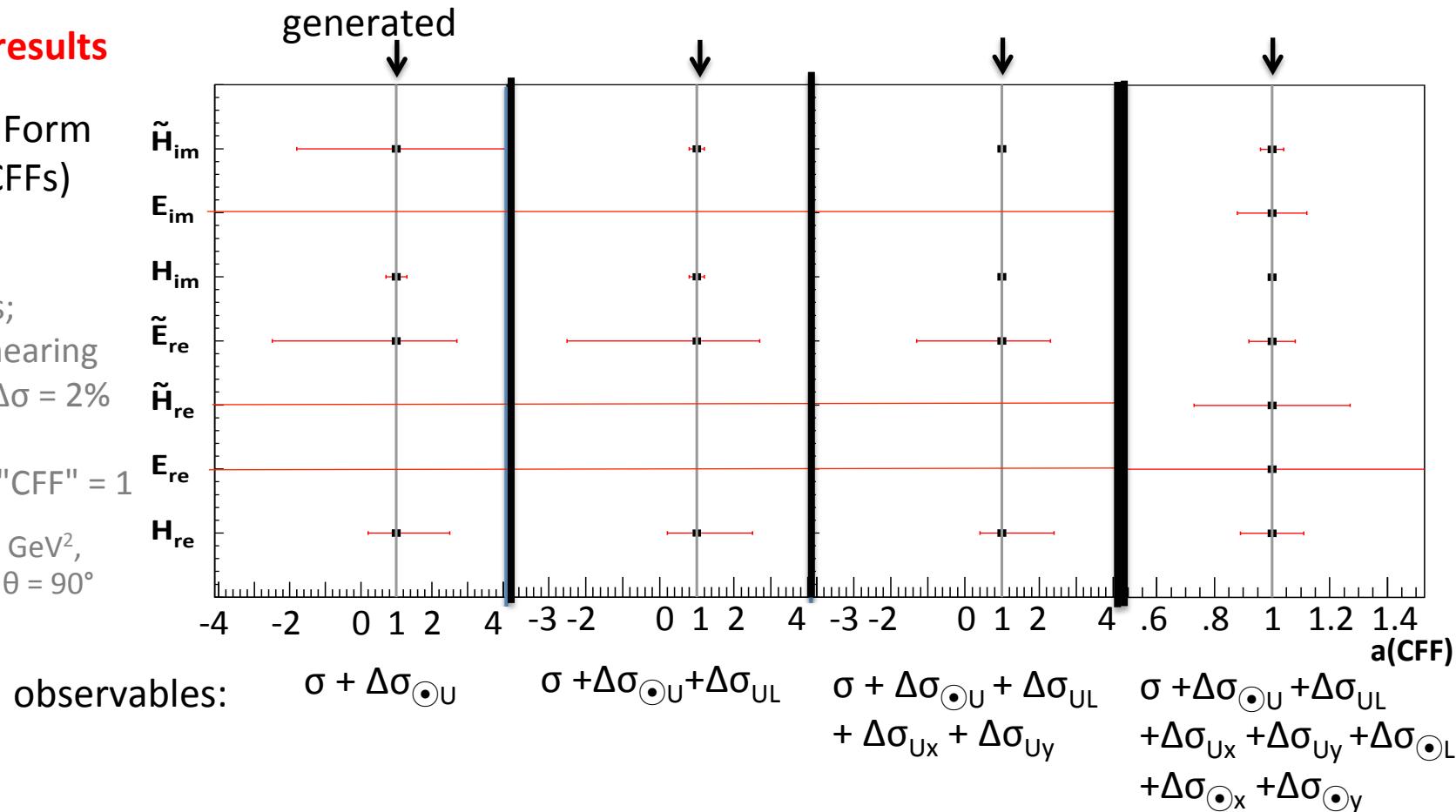
Set of results

Compton Form
Factors (CFFs)

simulations;
without smearing
 $\delta\sigma = 5\%$, $\delta\Delta\sigma = 2\%$

generated "CFF" = 1

$\xi=0.2$, $Q'^2 = 7 \text{ GeV}^2$,
 $-t=0.4 \text{ GeV}^2$, $\theta = 90^\circ$



- underconstrained system: some CFFs are extracted: $\Im(\mathcal{H})$
- 8 independant observables, 7 CFFs: all CFFs are extracted
- single spin asymmetries $\propto \text{Im}T \Rightarrow \text{Im}(\text{CFFs})$ are extracted with smaller error bars

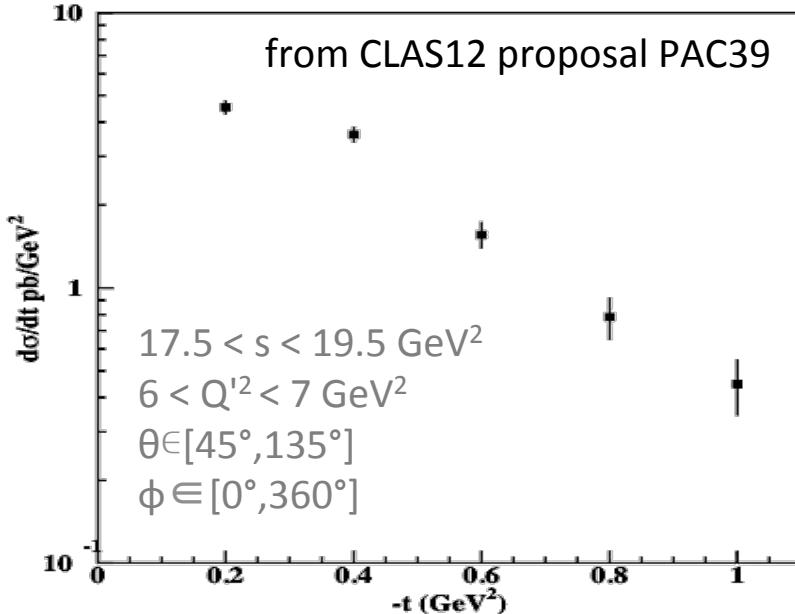
CFFs can be extracted from TCS fits

Experimental perspectives at JLab

CLAS12 accepted proposal PAC 39

projections for cross section

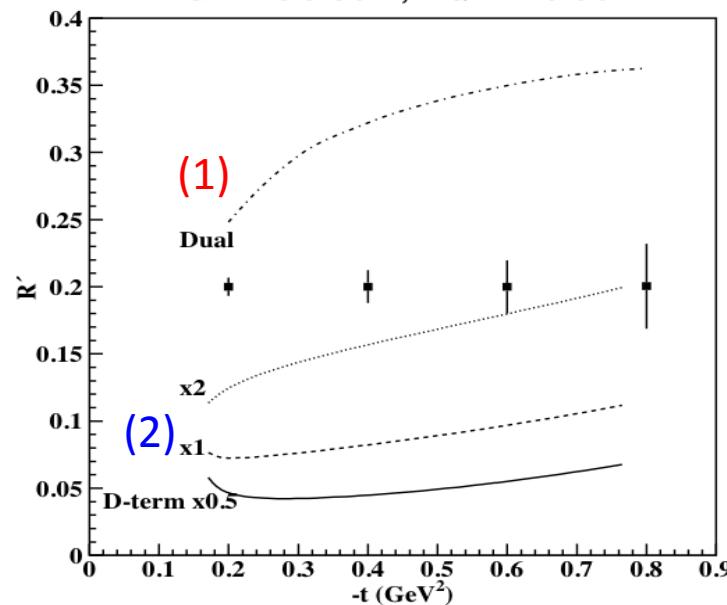
$$s = 18.5 \text{ GeV}^2, Q'^2 = 6.5 \text{ GeV}^2$$



100 days, $A \approx 0.2$, $L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, $E(e^-) = 11 \text{ GeV}$,
quasi-real photons

projection for R ratio

$$\langle s \rangle = 15.5 \text{ GeV}^2, \langle Q'^2 \rangle = 5 \text{ GeV}^2$$



(1) Polyakov, Shuvaev. 2002, hep-ph/0207153.

(2) Radyushkin. Phys. Rev., 1999, hep-ph/9805342

- 1st measurement
- Real part of CFFs

$$R = \frac{2 \int_0^{2\pi} d\varphi \cos \varphi \frac{dS}{dQ'^2 dt d\varphi}}{\int_0^{2\pi} d\varphi \frac{dS}{dQ'^2 dt d\varphi}} \quad \text{with} \quad \frac{dS}{dQ'^2 dt d\varphi} = \int_{\pi/4}^{3\pi/4} d\theta \frac{L(\theta, \varphi)}{L_0(\theta)} \frac{d\sigma}{dQ'^2 dt d\theta d\varphi}$$

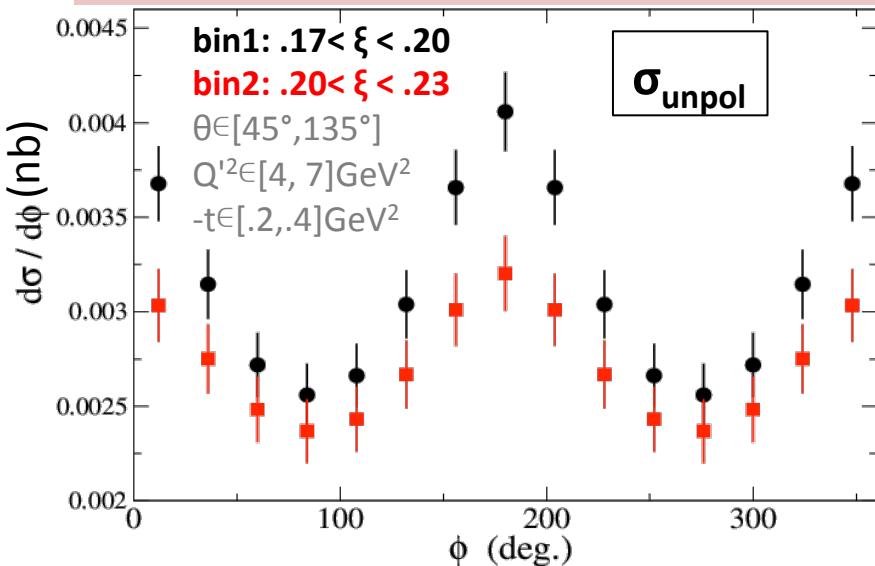
BH propagators
unpol. cross section

Experimental perspectives at JLab

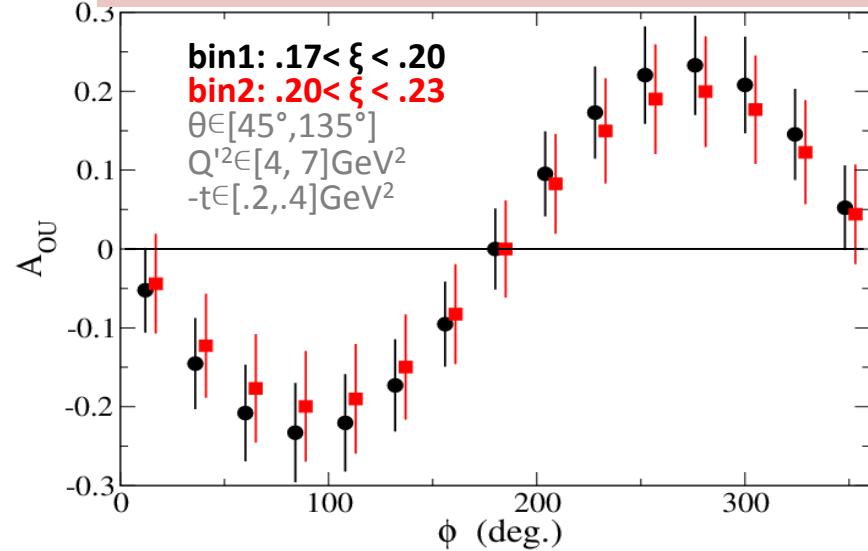
CLAS12 configuration

100 days, $A \approx 0.2$, $L = 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, $E(e^-) = 11 \text{ GeV}$,
quasi-real photons + bremsstrahlung on 15 cm LH2 target

expected rates with accepted experiment



A_{OU} : need a circular beam polarisation



~5% stat: justification of $\delta\sigma = 5\%$ for the fits, the observables are measurable

Work ongoing for a new proposal at JLab:

- new observables (polarized beam and/or target)
- TCS off the neutron (GPD E and flavor separation)
- choice of experimental Hall at JLab
- improvement of statistic (target lenght, radiator for a polarized bremsstrahlung beam...)

Summary

Calculations of unpolarized + beam and/or target polarized cross sections¹

- Single spin asymmetries (beam or target) most favorable for GPDs
- TCS off the neutron: flavor separation, GPD E
- Some higher twist taken into account

Fits on pseudo-data

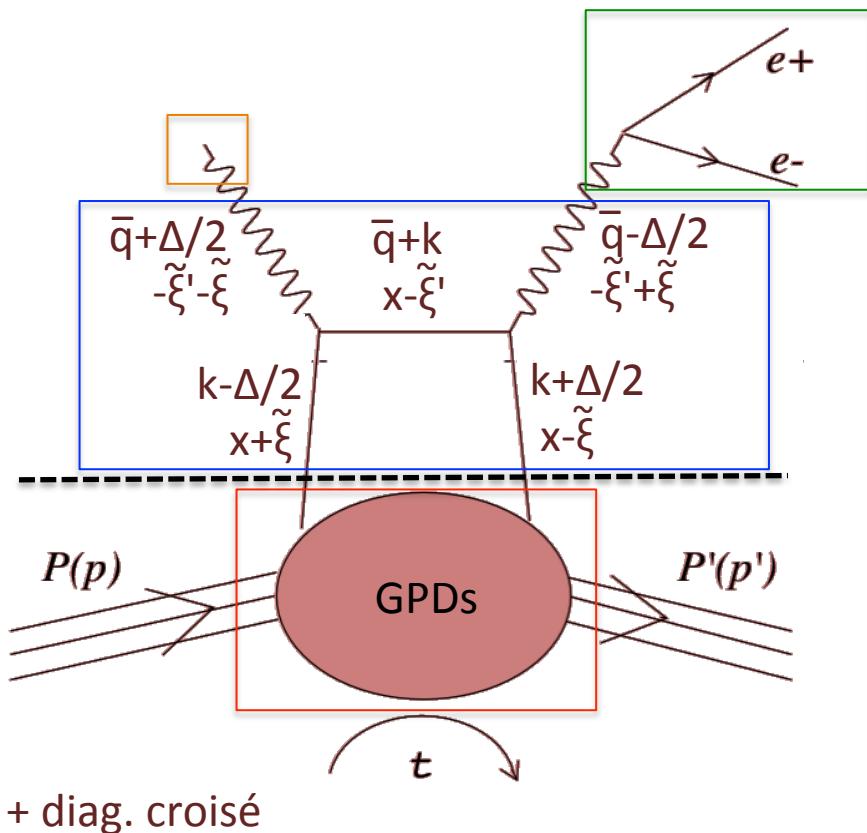
- CFFs can be extracted with TCS
- Comparison with DVCS: evaluation of higher order and higher twist effect (ongoing)

Experimental perspectives at JLab

- Accepted experiment at CLAS12, LOI for SOLID
- New proposal? (ongoing)

¹MB, M. Guidal, hep-ph/1412.2036

Amplitude du TCS



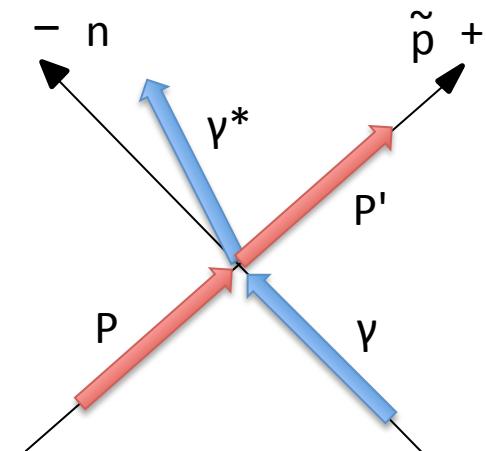
Référentiel du "cône de lumière"

- \bar{q} et P collinéaires selon l'axe z
- vecteurs de Sudakov \tilde{p}^μ et n^μ
- $\tilde{\xi}$ et $\tilde{\xi}'$ = composantes "+" de Δ et \bar{q}

$$\begin{cases} P = \frac{1}{2}(p + p') \\ \bar{q} = \frac{1}{2}(q + q') \\ \Delta = (p' - p) = (q' - q) \end{cases}$$

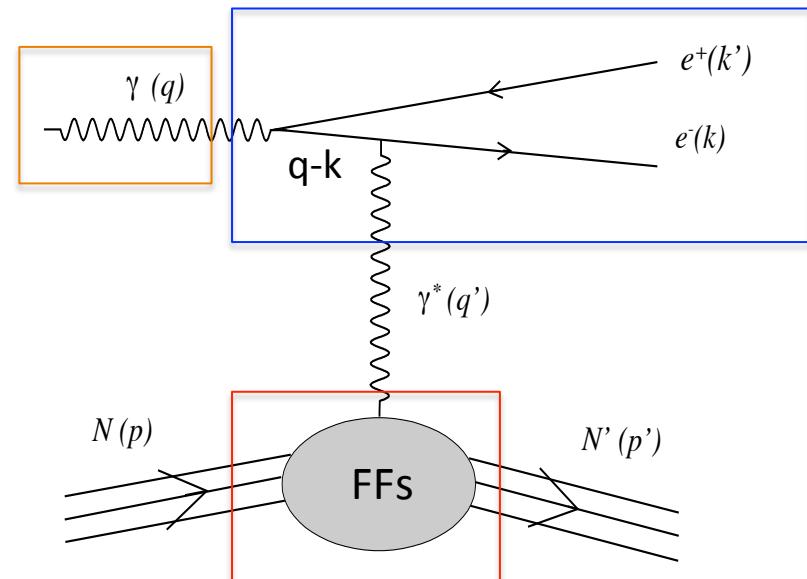
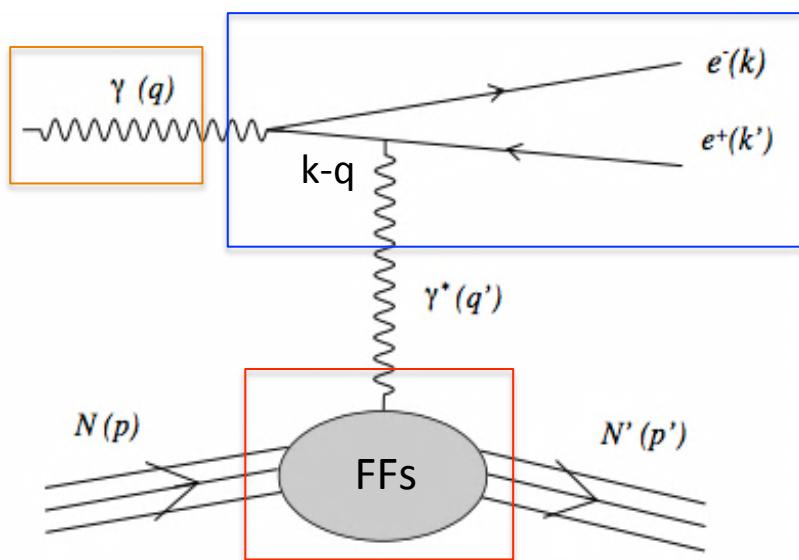


$$\begin{cases} P^\mu = \tilde{p}^\mu + \frac{\bar{m}^2}{2} n^\mu \\ \Delta^\mu = -2\tilde{\xi}\tilde{p}^\mu + \tilde{\xi}\bar{m}^2 n^\mu + \Delta_\perp^\mu \\ \bar{q}^\mu = -\tilde{\xi}'\tilde{p}^\mu - \frac{\bar{q}^2}{2\tilde{\xi}'} n^\mu \end{cases}$$



$$T^{TCS} = \left[-\frac{e^3}{q'^2} u(k) \gamma^\nu v(k') \epsilon^\mu(q) \left[\frac{1}{2} (-g_{\mu\nu})_\perp \int_{-1}^1 dx \left(\frac{1}{x - \tilde{\xi}' + i\epsilon} + \frac{1}{x + \tilde{\xi}' - i\epsilon} \right) \cdot \left(H(x, \tilde{\xi}, t) u(p') \not{p} u(p) + E(x, \tilde{\xi}, t) u(p') i\sigma^{\alpha\beta} n_\alpha \frac{\Delta_\beta}{2M} u(p) \right) \right. \right. \\ \left. \left. - \frac{i}{2} (\epsilon_{\nu\mu})_\perp \int_{-1}^1 dx \left(\frac{1}{x - \tilde{\xi}' + i\epsilon} - \frac{1}{x + \tilde{\xi}' - i\epsilon} \right) \cdot \left(\tilde{H}(x, \tilde{\xi}, t) u(p') \not{p} \gamma_5 u(p) + \tilde{E}(x, \tilde{\xi}, t) u(p') \gamma_5 \frac{\Delta \cdot n}{2M} u(p) \right) \right] \right]$$

Amplitude du Bethe-Heitler et section efficace



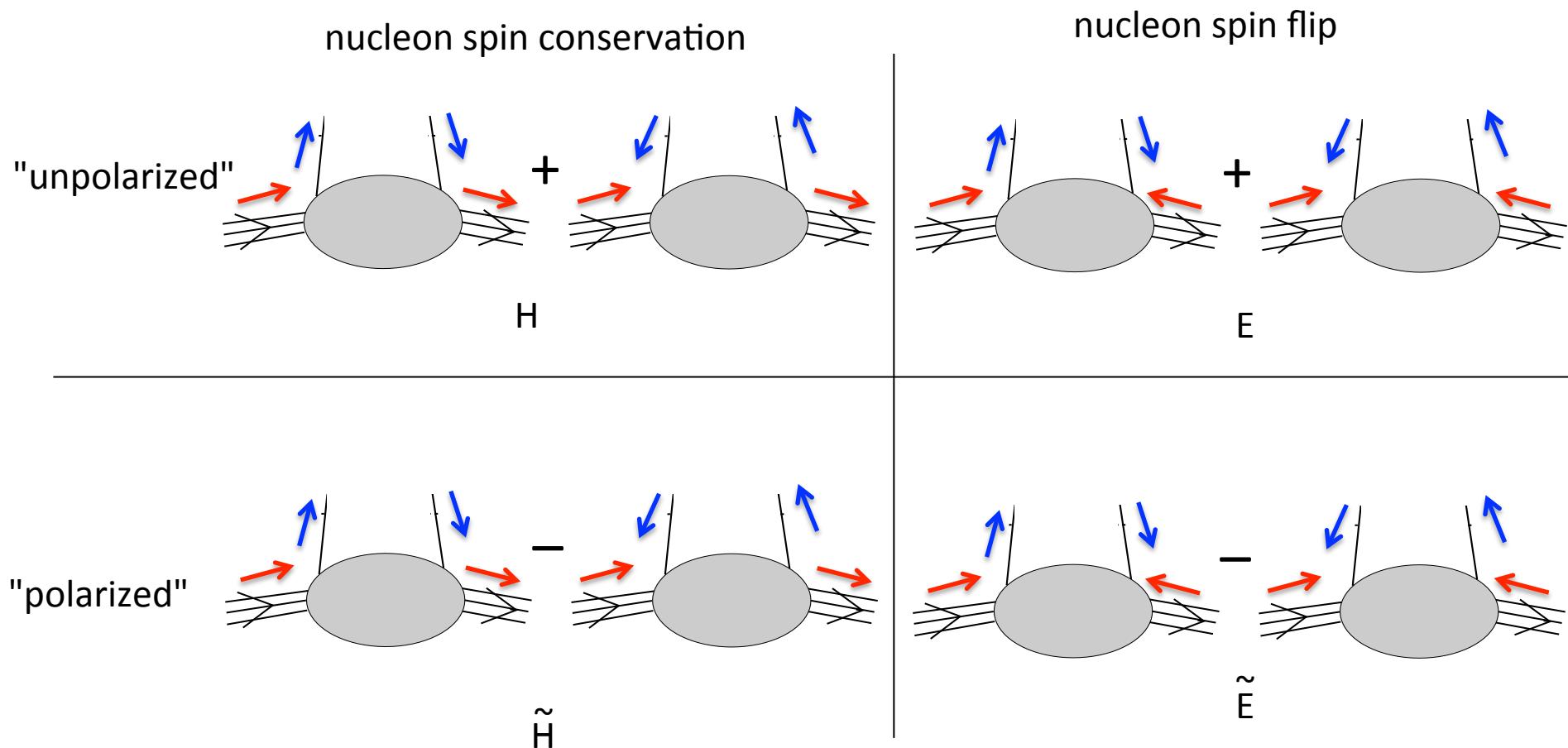
$$T^{BH} = -\frac{e^3}{\Delta^2} u(p') \left(\gamma^v F_1(t) + \frac{i\sigma^{\nu\rho}\Delta_\rho}{2M} F_2(t) \right) u(p) \boxed{\epsilon^\mu(q)} u(k) \left(\gamma_\mu \frac{k-q}{(k-q)^2} \gamma_\nu + \gamma_\nu \frac{q-k'}{(q-k')^2} \gamma_\mu \right) v(k')$$

$$\frac{d^4\sigma}{dQ'^2 dt d\Omega} (\gamma p \rightarrow p' e^+ e^-) = \frac{1}{(2\pi)^4} \frac{1}{64} \frac{1}{(2ME_\gamma)^2} | T^{BH} + T^{TCS} |^2$$

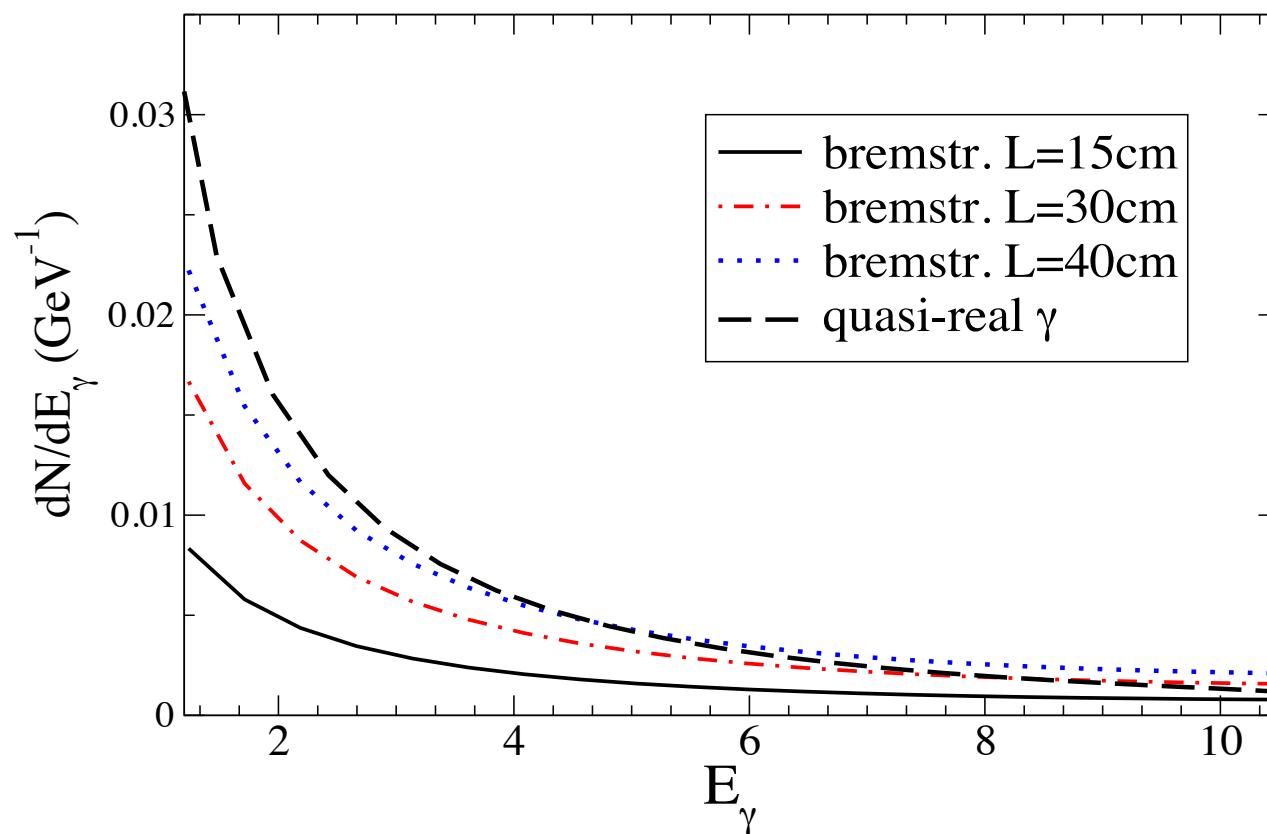
Generalized Parton Distributions

GPDs for TCS off the nucleon at leading twist

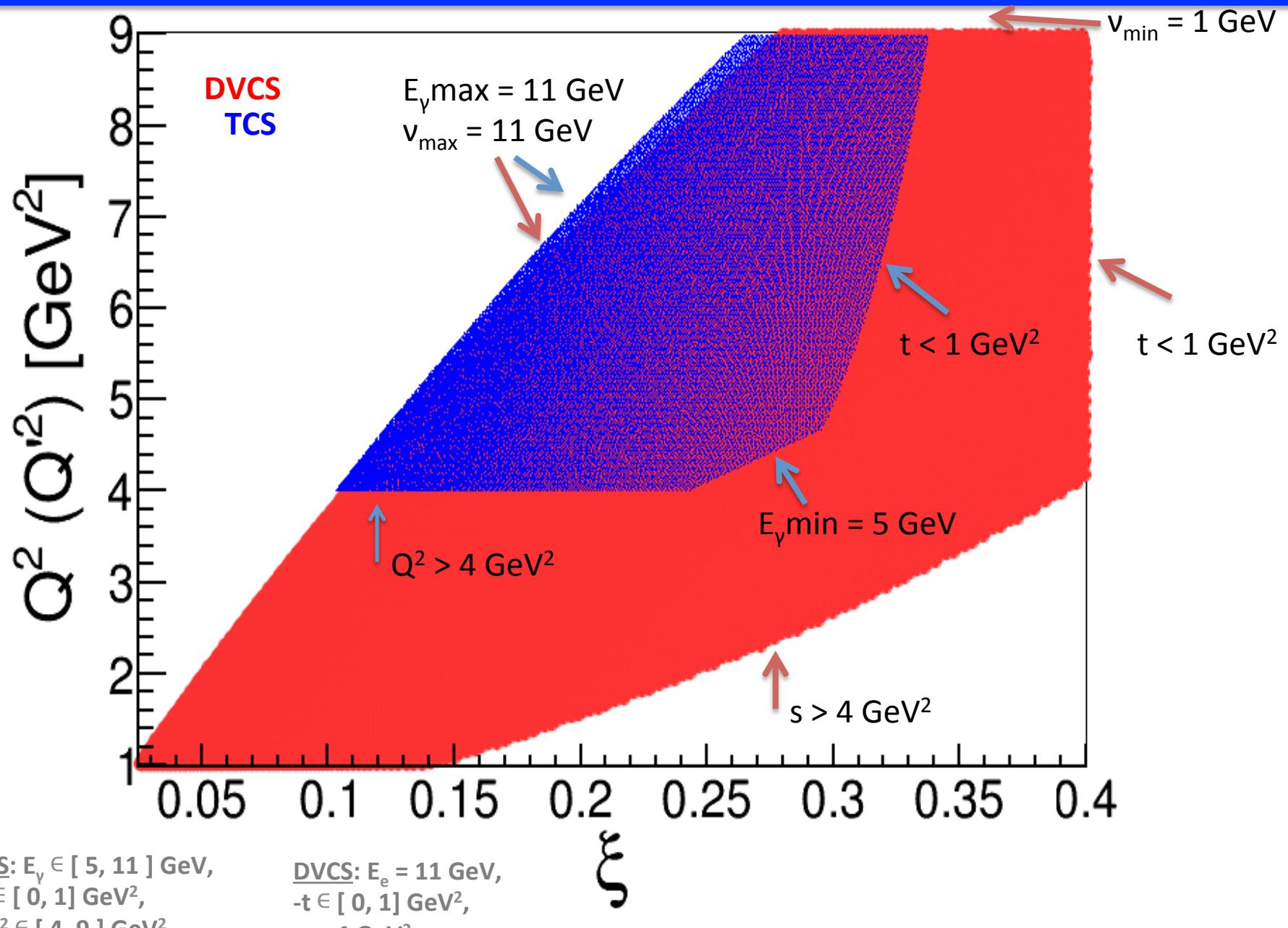
quark helicities (with mass = 0) and nucleon spin relative orientations



Equivalent photon flux (electron beam),
 $E=11 \text{ GeV}$, $L=10^{35} \text{ cm}^{-2}\text{s}^{-1}$



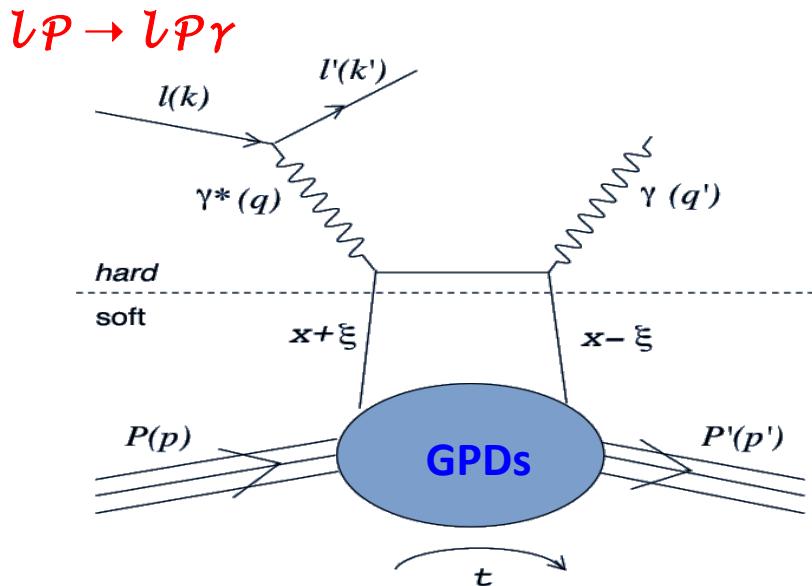
DVCS and TCS phase space at JLab 12 GeV



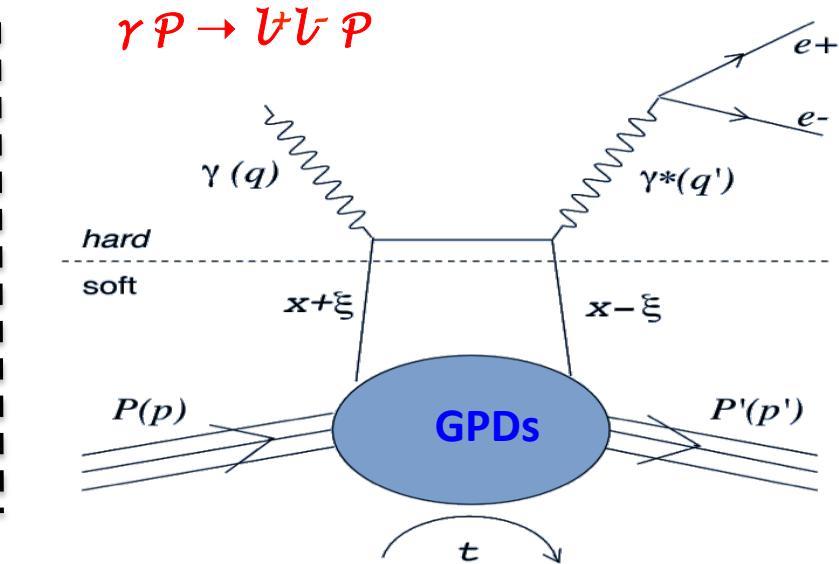
TCS and DVCS

Deeply Virtual Compton Scattering

spacelike



timelike

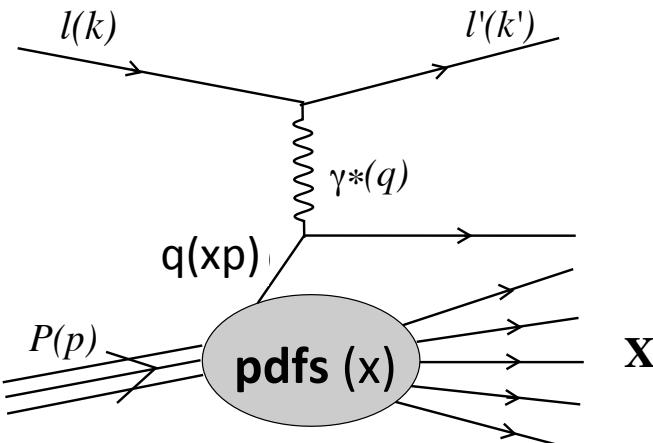


DVCS: Deep Virtual Compton Scattering

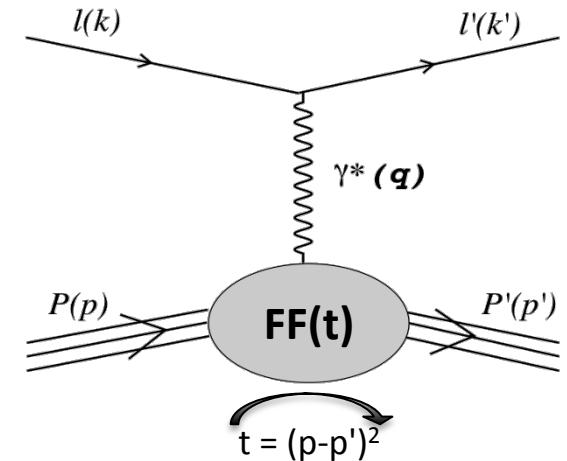
TCS: Time-like Compton Scattering

GPDs = Generalized Parton Distributions (the same)

Timelike Compton Scattering

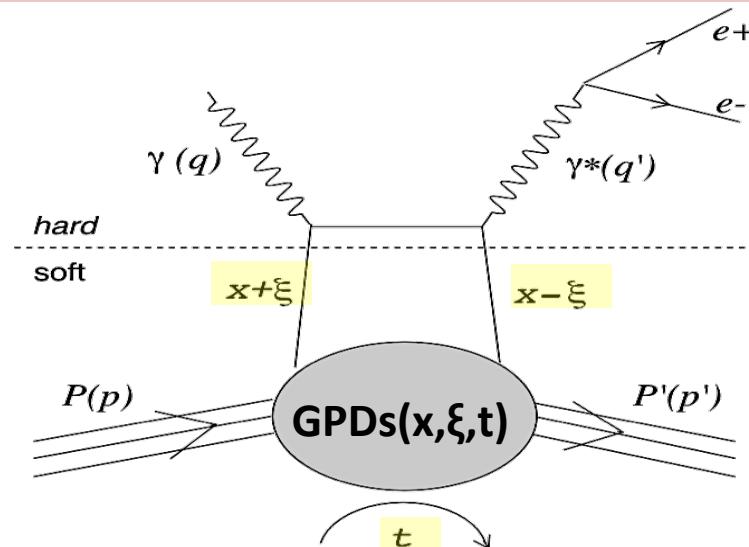


Deep Inelastic Scattering $lP \rightarrow lX$
 Parton Distributions pdf (x)
 \Rightarrow longitudinal momentum fraction x



Elastic Scattering $lP \rightarrow lP$
 Form Factors FF ($t=Q^2$)
 \Rightarrow transverse charge densities

Correlation between longitudinal momentum and transverse charge densities



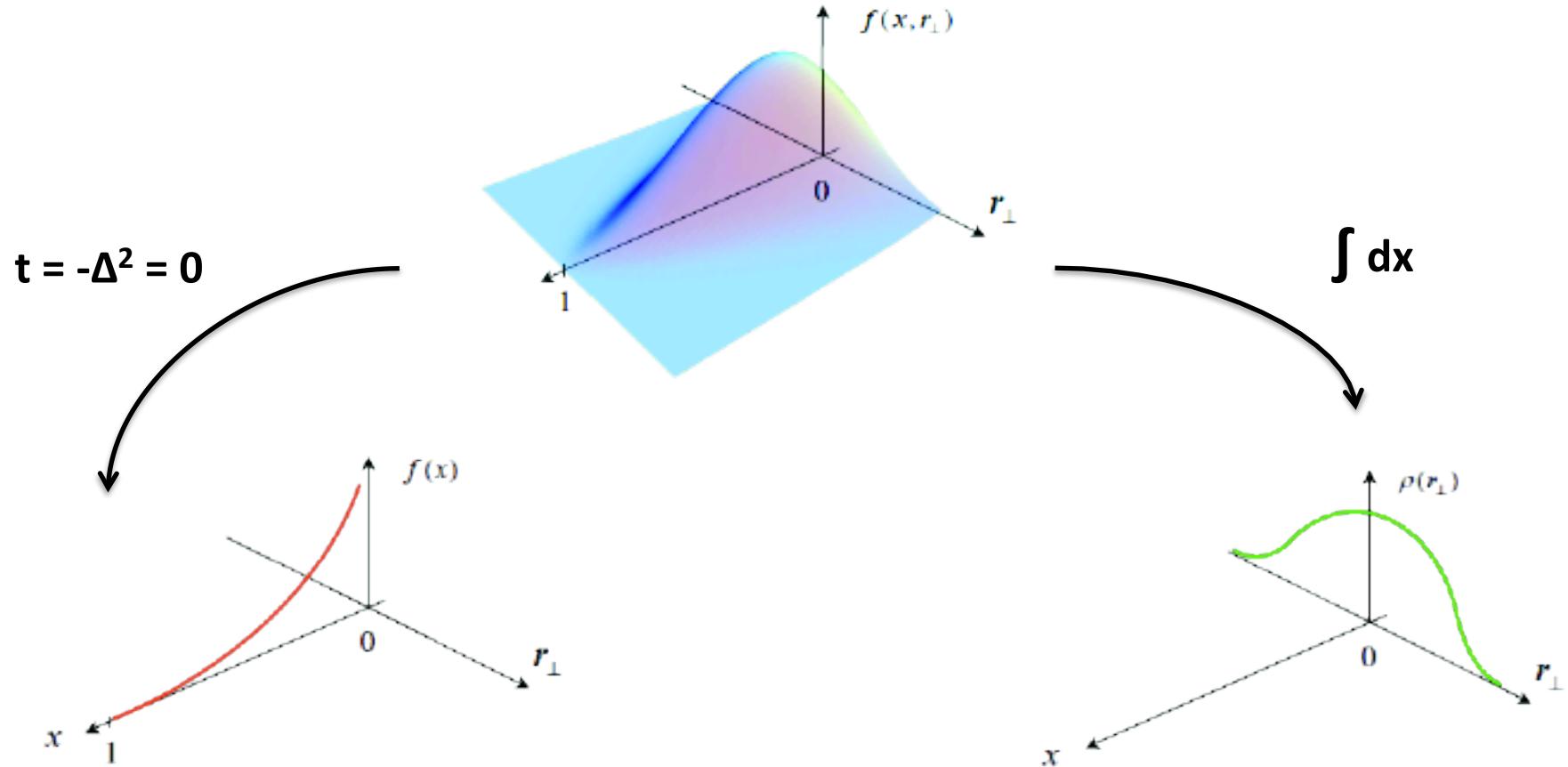
$Q^2 > 1 \text{ GeV}^2$: hard scale
 $t = (P-P')^2 \ll Q^2$:
 partonic structure
 x: average quark longitudinal
 momentum fraction
 ξ : longitudinal mom. transfert

$\gamma P \rightarrow l\bar{l} P$
**Timelike Compton
 Scattering TCS**

Generalized Parton
 Distributions (GPDs)
 $\Rightarrow H(x, b_\perp \dots)$
 \Rightarrow Ji sum rule for spin...

Links

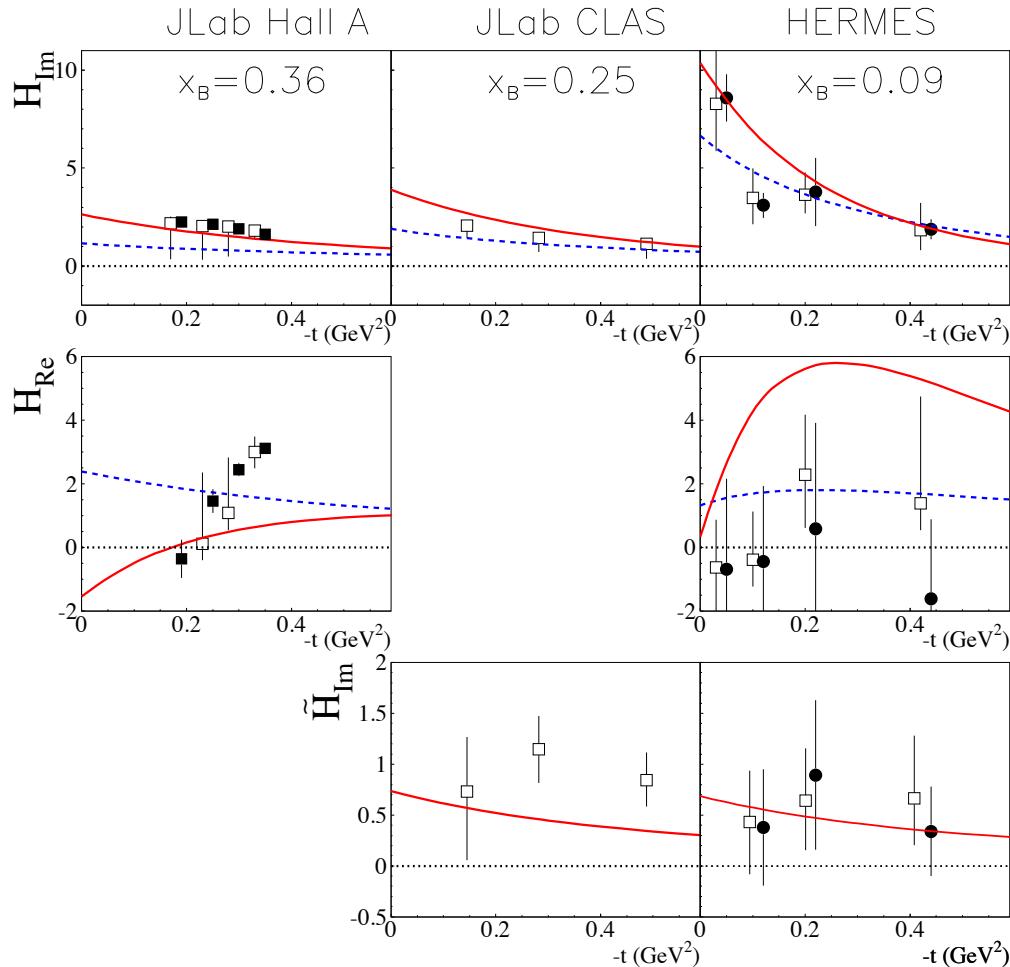
Generalized Parton Distributions (GPD) $H(x, \xi, t)$



Parton Distributions
pdf $q(x)$

Form Factors
FF $F(t)$

Fits avec le DVCS



Données expérimentales publiées
(JLab, HERMES, H1, ZEUS)

- cette méthode, VGG¹
- GPD H, "méthode hybride"²
- "mapping" linéaire³
- VGG**
- KM**

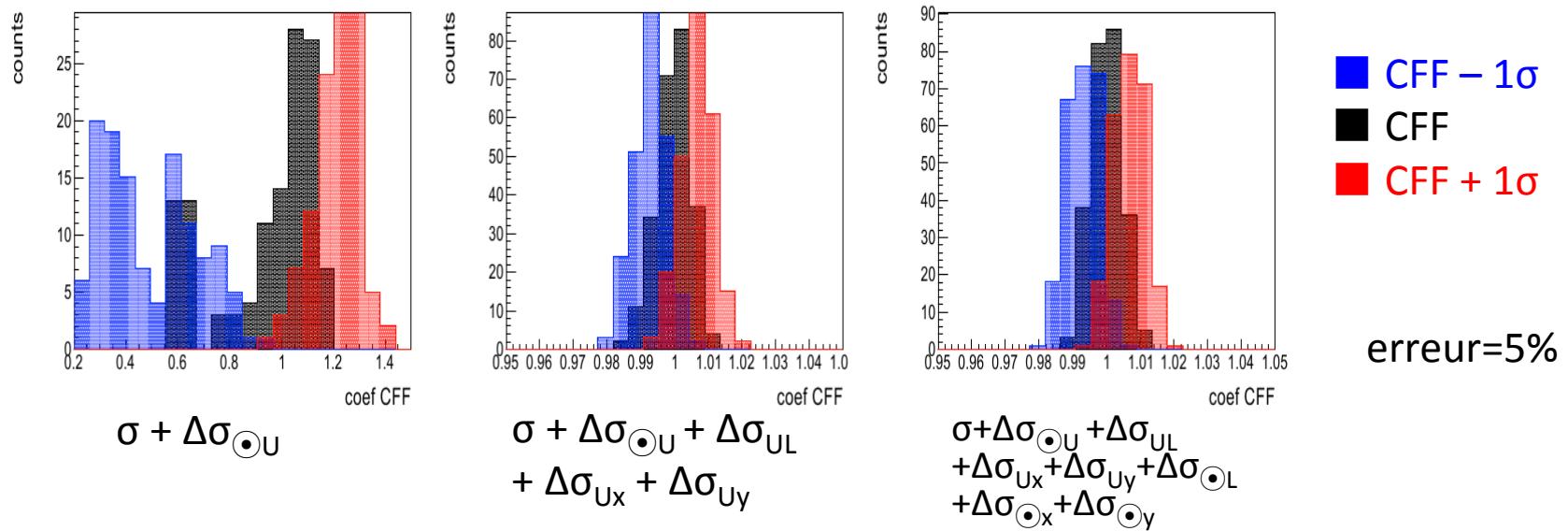
- Résultats compatibles avec les différentes méthodes
- Principales différences dans les modèles: parties réelles des CFFs

Nouveau: interprétation incertitudes CFFs, études systématiques des sources d'instabilité des résultats, validation de l'extraction des CFFs avec des fits sous-constraints

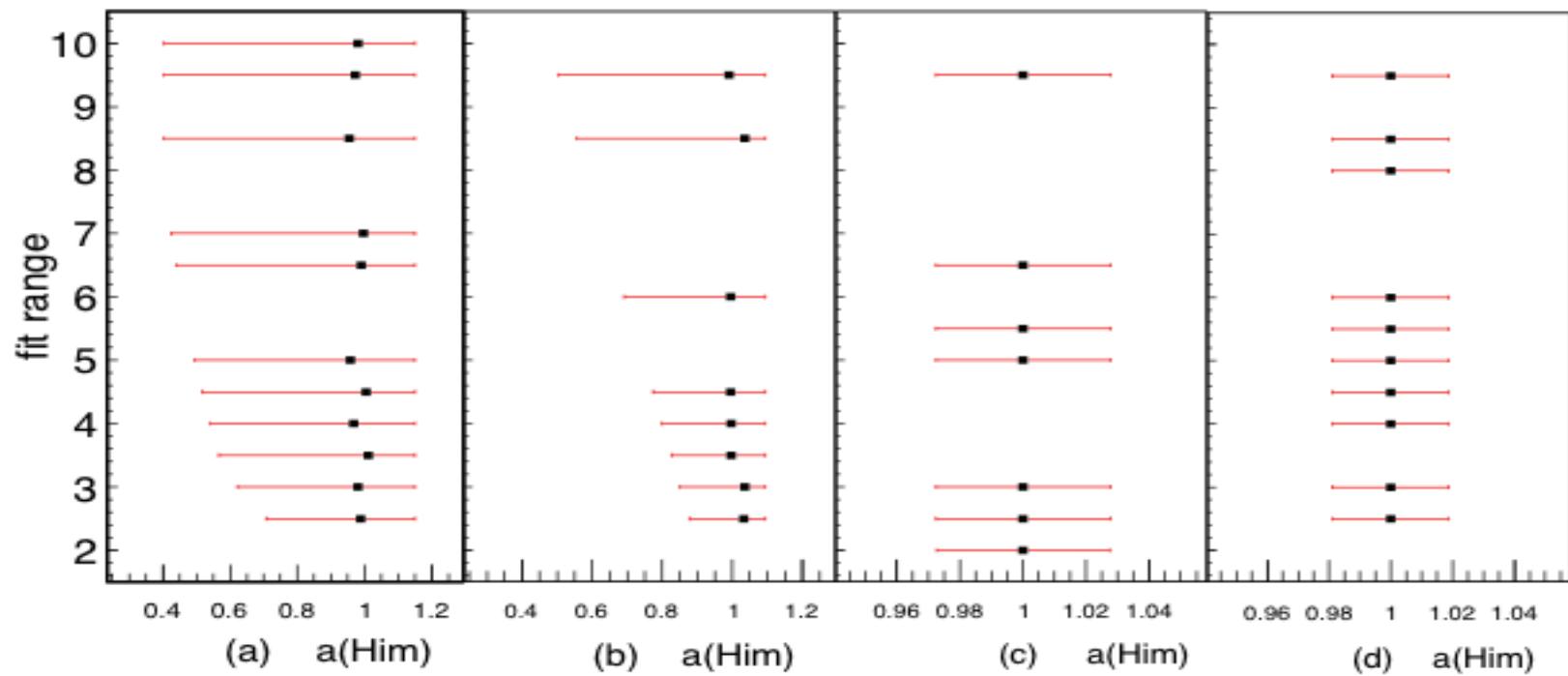
Smearing effects

Results with a gaussian smearing in simulations

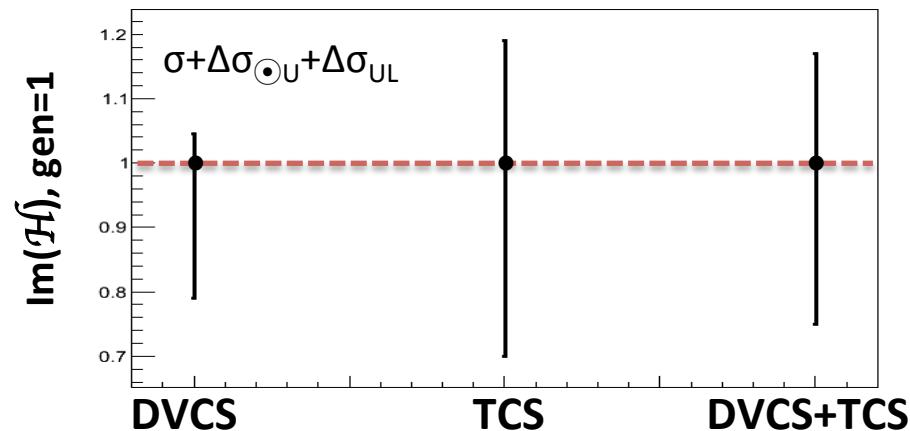
- ◊ comparable to the results of fitting experimental observables



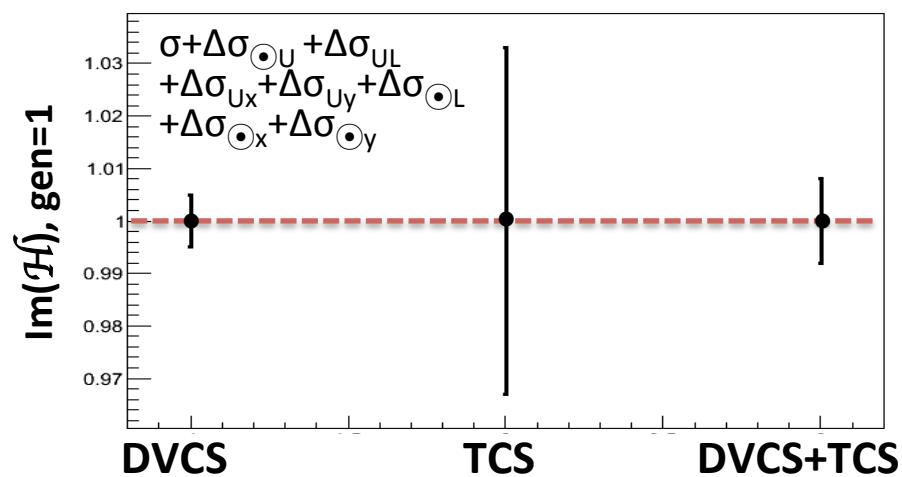
CFF extraction is still possible even with smearing effects and for underconstrained fits
asymmetric error bar for underconstrained fits



Fits with DVCS and TCS together



Amplitudes au twist 2 = complexes conjugués:
mêmes CFFs avec $|\xi|_{\text{DVCS}} = |\xi|_{\text{TCS}}$ (simulations)



⇒ Observables non indépendantes,
contraintes sur les mêmes CFFs

⇒ Incertitudes sur les CFFs:
 $\delta(\text{DVCS}) < \delta(\text{DVCS+TCS}) < \delta(\text{TCS})$

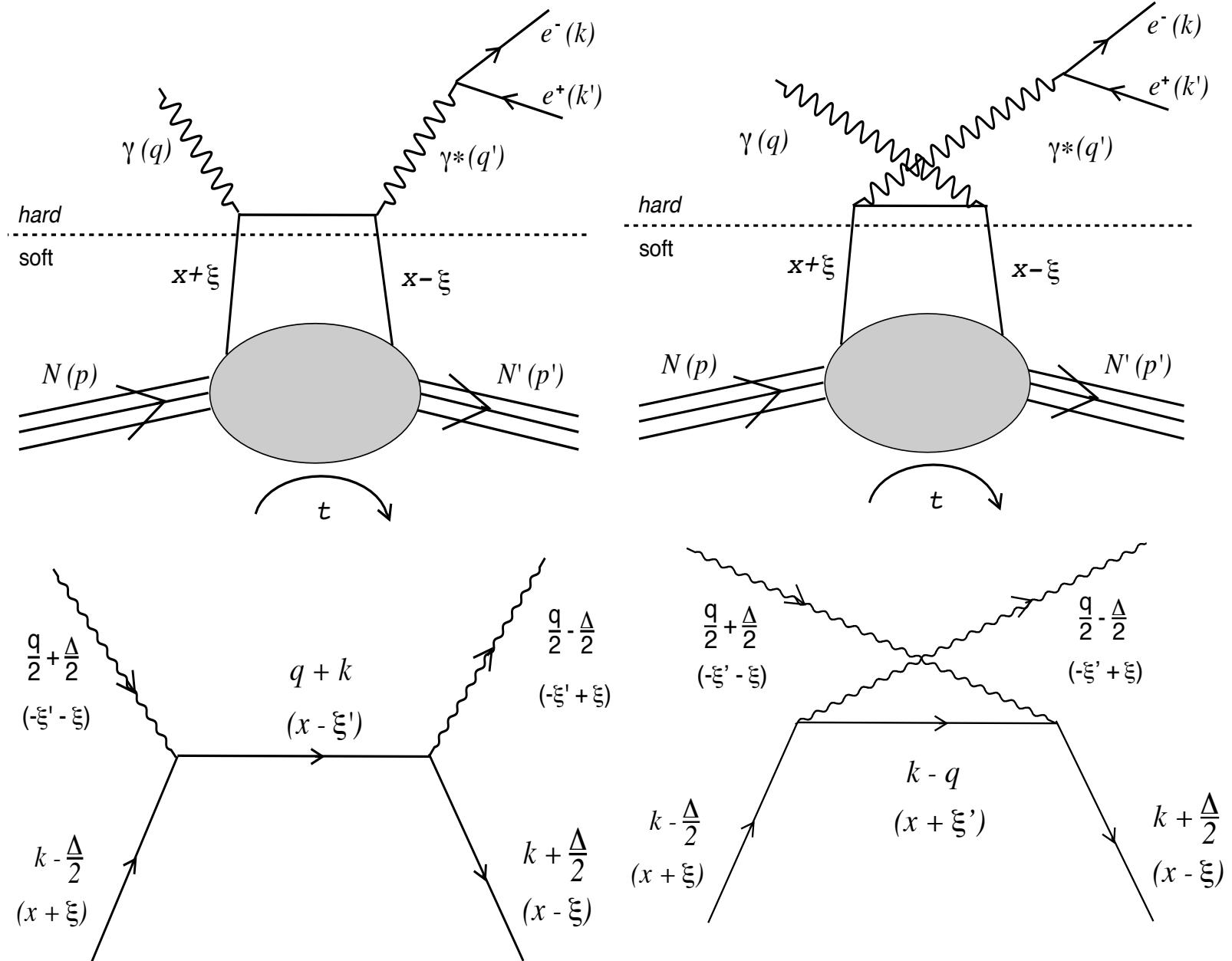
⇒ Le TCS ne permet pas de mieux
construire le système (vs DVCS)

$$\xi = 0.2, Q'^2 = 7 \text{ GeV}^2, -t = 0.4 \text{ GeV}^2, \theta = 90^\circ$$

Intérêts: étude des effets de twist et d'ordre supérieur

- ⇒ Évaluation possible à partir de l'élargissement des distributions
- ⇒ Requiert une bonne précision sur les observables DVCS et TCS

Leading twist TCS diagrams, hard part



DDVCS

